Selecting and Evaluating Indicators for the California Current

Selecting Ecosystem Indicators for the California Current

What is an Ecosystem Indicator?

Ecosystem indicators are quantitative biological, chemical, physical, social, or economic measurements that serve as proxies of the conditions of attributes of natural and socioeconomic systems (e.g., Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Ecosystem attributes are characteristics that define the structure, composition, and function of the ecosystem that are of scientific or management importance but insufficiently specific or logistically challenging to measure directly (Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Thus indicators provide a practical means to judge changes in ecosystem attributes related to the achievement of management objectives. They can also be used for predicting ecosystem change and assessing risk.

Ecosystem indicators are often cast in the Driver-Pressure-State-Impact-Response (DPSIR) framework—an approach that has been broadly applied in environmental assessments of terrestrial and aquatic ecosystems, including NOAA's IEA (Levin et al. 2008). Drivers are factors that result in pressures that cause changes in the system. Natural and anthropogenic forcing factors are considered. An example of the former is climate conditions and examples of the latter include human population size in the coastal zone and associated coastal development, the desire for recreational opportunities, and so forth. In principle, human driving forces can be assessed and controlled, whereas natural environmental changes cannot be controlled but are accounted for in management.

Pressures are factors that cause changes in state or condition. They can be mapped to specific drivers. Examples include coastal pollution, habitat loss and degradation, and fishing. Coastal development results in increased coastal armoring and the degradation of associated nearshore habitat. State variables describe the condition of the ecosystem (including physical, chemical, and biotic factors). Impacts comprise measures of the effect of change in these state variables such as loss of biodiversity, declines in productivity and yield, etc. Impacts are measured with respect to management objectives and the risks associated with exceeding or returning to below these targets and limits.

Responses are the actions (regulatory and otherwise) taken in response to predicted impacts. Forcing factors under human control trigger management responses when target values are not met as indicated by risk assessments. Natural drivers may require adaptational response to minimize risk. For example, changes in climate conditions that in turn affect the basic productivity characteristics of a system may require changes in ecosystem reference points that reflect the shifting environmental states.

Ideally, indicators should be identified for each step of the DPSIR framework such that the full portfolio of indicators can be used to assess ecosystem condition as well as the processes and mechanisms that drive ecosystem health. State and impact indicators are preferable for identifying the seriousness of an environmental problem, but pressure and response indicators are needed to know how best to control the problem (Niemeijer and de Groot 2008). In 2010 we focused primarily on indicators of ecosystem state (EBM components), while future California Current IEA iterations will address and evaluate indicators of drivers and pressures. Indicators can be used as measurement endpoints for examining alternative management scenarios in ecosystem models (Appendix A) or in emerging analyses to predict or anticipate regime shifts (Appendix B).

Specific Goals Will Determine the Suite of Indicators

It is a significant challenge to select a suite of indicators that accurately characterizes the ecosystem while also being relevant to policy concerns. A straightforward approach to overcoming this challenge is to employ a framework that explicitly links indicators to policy goals (Harwell et al. 1999, EPA 2002). This type of framework organizes indicators in logical and meaningful ways in order to assess progress towards policy goals. We use the framework established by Levin et al. (2010b) as guidance. Our framework begins with the set of seven EBM components (Figure 2). Each EBM component represents a discrete segment of the ecosystem that reflects societal goals or values and is relevant to the policy goals of NMFS. Each component is then characterized by key attributes, which describe fundamental aspects of each goal. Finally, we map indicators onto each key attribute. In this report, we focused on aspects of four ecosystem components: groundfish (wild fisheries component), salmon (wild fisheries and protected resources components), green sturgeon (*Acipenser medirostris*) (protected resources component), and ecosystem health (ecosystem health component).

Groundfish

Groundfish are generally defined as a community of fishes that are closely associated with the ocean bottom. In the CCLME, some of the better known species include the rockfishes (Scorpaenidae), flatfishes (Pleuronectidae and Bothidae), sculpins (Cottidae), Pacific hake, sablefish (*Anoplopoma fimbria*), greenlings and lingcod (Hexagrammidae), skates (Rajidae), and benthic sharks (PFMC 2008a). Similar to most fishes, many groundfish species have a planktonic larval and young-of-year life history stage in which young fish inhabit surface waters and feed on a diet of zooplankton. After a few months in the plankton, most species settle to the bottom and remain there for the rest of their lives. Groundfish vary across a wide range of trophic levels and inhabit all types of habitats (e.g., rocky, sandy, muddy, kelp) from the intertidal zone to the abyss.

This community of fishes constitutes a large biomass in the CCLME and provides the economic engine for coastal communities in Washington, Oregon, and California. The Pacific Fishery Management Council (PFMC) manages a subset of groundfish species that are typically captured during fishing operations along the U.S. West Coast. Those species caught in the Pacific groundfish trawl fishery were worth approximately $40 million in 2009 (NOAA press release 2010). Thus understanding how groundfish populations fare over time is of great interest to ecosystem managers and the coastal communities that derive much of their wealth from this assemblage of fishes.

Salmon

Two species make up the vast proportion of salmon abundance within the CCLME: Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) (Healy 1991). Salmon spawn in freshwater where their eggs and juveniles spend up to a year before migrating to sea. Ocean conditions at the time of sea entry are extremely important to the survival and ultimate abundance of fish in the fishery and the spawning population (Pearcy 1992, Beamish and Mahnken 2001). Chinook salmon generally spend 2–5 years at sea before returning to their natal stream to spawn (Quinn 2005). Coho spend approximately 1.5 years at sea (Sandercock 1991, Beamish et al. 2004).

Chinook salmon make up one of the most valuable and prized fisheries within the CCLME. For example, in 2004 and 2005 there were 5 million and 7.1 million pounds of Chinook salmon landed in California, respectively valued at $12.8 million and $17.8 million (Lindley et al. 2009a). Additionally, the associated economic benefits from the fisheries are great. During 2008 and 2009 a population collapse of Chinook salmon and the poor status of many West Coast coho salmon populations necessitated the closure of the salmon fishery in California waters (Lindley et al. 2009b). This translated to more than $200 million in losses and a U.S. Congressional appropriation of $170 million for disaster relief (Lindley et al. 2009b).

Green sturgeon

Green sturgeon are long-lived, slow growing fish with a K-selected life history (MacArthur and Wilson 1967, Moyle 2002). Mature females can reach lengths of more than 2 m and do not mature until at least 15 years old (Adams et al. 2002). Along the coast are two distinct stocks: a northern stock from the Rogue and Klamath rivers and a southern stock from the Sacramento River (Adams et al. 2002). Generally, little is known about the biology, abundance, or condition of these stocks. Much like salmon, green sturgeon spawn in freshwater where juveniles can reside for up to 4 years (Adams et al. 2002). Once juveniles migrate to sea, they can undertake extensive migrations along the Pacific coast (Adams et al. 2002). Critical habitat required to complete the life cycle of green sturgeons has been identified as the shelf waters from Monterey Bay, California, to Vancouver Island, British Columbia, as well as the river and estuarine waters of rivers associated with spawning and rearing (50 CFR Part 226).

Based on trends in historical fisheries, during which catches indicated a much greater abundance than currently observed and extensive degradation of freshwater habitats, NMFS listed the southern stock as threatened (Adams et al. 2007).

Ecosystem health

Rapport et al. (1985) suggested that the responses of stressed ecosystems were analogous to the behavior of individual organisms. Just as the task of a physician is to assess and maintain the health of an individual, resource managers are charged with assessing and, when necessary, restoring ecosystem health. This analogy is rooted in the organismic theory of ecology advocated by F. E. Clements more than 100 years ago, and is centered on the notion that ecosystems are homeostatic and stable, with unique equilibria (De Leo and Levin 1997). In reality, however, disturbances, catastrophes, and large-scale abiotic forcing create situations where ecosystems are seldom near equilibrium. Indeed, ecosystems are not "superorganisms"—they are open and dynamic with loosely defined assemblages of species (Levin 1992). Consequently, simplistic analogies to human health break down in the face of the complexities of the nonequilibrial dynamics of many ecological systems (Orians and Policansky 2009). Even so, the term "ecosystem health" has become part of the EBM lexicon and resonates with stakeholders and the general public (Orians and Policansky 2009). In addition ecosystem health is peppered throughout the literature on ecosystem indicators. Thus while we acknowledge the flaws and limitations of the term, we use it here because it is familiar and salient in the policy arena. In the CCLME application, ecosystem health is defined specifically by the key attributes described below.

Key Attributes of EBM Components

Key attributes are ecological characteristics that specifically describe some relevant aspect of each EBM component. They are characteristic of the health and functioning of each EBM component, and they provide a clear and direct link between the indicators and components. For each of the first three components (groundfish, salmon, and green sturgeon), we identified the same key attributes (Levin et al. 2010b): population size and population condition. For the component ecosystem health, we identified and focused on two key attributes: community composition, and energetics and material flows (Table 1).

Groundfish, salmon, and green sturgeon

Population size—Monitoring population size in terms of total number or total biomass is important for management and societal interests. For example, abundance estimates are used to track the status of threatened and endangered species and help determine whether a species is recovering or declining. Accurate population biomass estimates of targeted fisheries species are used to assess stock viability and determine the number of fish that can be sustainably harvested from a region. While population size can be used to assess population viability, more accurate

Table 1. Selected key attributes for each goal. Relevant measures describe what each attribute means (e.g., population size is represented by the number of individuals in a population or the total biomass).

Goal	Key attribute	Relevant measures
Groundfish, salmon, and green sturgeon	Population size	Number of individuals or total biomass, population dynamics
	Population condition	Measures of population or organism condition including: age structure, population structure, phenotypic diversity, genetic diversity, organism condition
Ecosystem health	Community composition	Ecosystem structure: species diversity, trophic diversity, functional redundancy, response diversity
	Energetics and material flows	Ecosystem function: primary production, nutrient flow/cycling

predictions of viability can be obtained by including the mechanisms responsible for the dynamics of the population. Population dynamics thus provide a predictive framework to evaluate the combined effect of multiple mechanisms of population regulation (e.g., birth and death rates, immigration, and emigration) to evaluate changes in abundance through time.

Population condition—Whereas the preceding attribute is concerned with measures of population size, there are instances when the health of the population may be of interest. For example, monitoring changes in population condition may presage an effect on population size or provide insight into long-term population viability. The dynamics of many populations are better understood through knowledge of population conditions such as organism condition, age structure, genetic diversity, phenotypic diversity, and population structure. Impaired condition of any or all of these subcategories indicates biological resources at risk. In addition, monitoring changes in population condition can be used to infer changes in environmental conditions.

Ecosystem health

Community composition—This attribute represents the structure of the ecosystem, describing the individual components and the relative extent of their potential interactions. Our definition of community composition includes species diversity, trophic level diversity, functional group redundancy, and response diversity. Species diversity encompasses species richness or the number of species in the ecosystem, and species evenness or how individuals or biomass are distributed among species within the ecosystem (Pimm 1984). Trophic diversity refers to the relative abundance or biomass of different primary producers and consumers within the ecosystem (EPA 2002). Consumers include herbivores, carnivores or predators, omnivores, and scavengers. Functional redundancy refers to the number of species characterized by traits that contribute to a specific ecosystem function, whereas response diversity describes how functionally similar species respond differently to disturbance (Laliberte and Legendre 2010). For example, an ecosystem containing several species of herbivores would be considered to have high functional redundancy with respect to the ecosystem function of grazing, but only if those herbivorous species responded differently to the same perturbation (e.g., trawling) would the food web be considered to have high response diversity.

Energetics and material flows—This attribute represents ecosystem function and includes ecological processes such as primary production and nutrient cycling, in addition to flows of organic and inorganic matter throughout an ecosystem. Primary productivity is the capture and conversion of energy from sunlight into organic matter by autotrophs, and provides the fuel fundamental to all other trophic transfers throughout the ecosystem. Material flows, or the cycling of organic matter and inorganic nutrients (e.g., nitrogen, phosphorus), describe the efficiency with which an ecosystem maintains its structure and function.

Evaluating Potential Indicators for the California Current: Groundfish and Ecosystem Health

Initial Selection of Indicators

There are numerous publications that cite indicators of species and ecosystem health in marine systems. For this report, we generally relied on several core references from the literature (Jennings and Kaiser 1998, Link et al. 2002, Rochet and Trenkel 2003, Fulton et al. 2005, Jennings 2005, Jennings and Dulvy 2005, Link 2005, Shin et al. 2005, Samhouri et al. 2009, Sydeman and Thompson 2010) to develop an initial list of potential indicators for each of the key attributes for two of the four EBM components: West Coast groundfish and ecosystem health. In many cases, indicators identified in the literature were chosen by the authors based on expert opinion or based on the context of the researchers' expertise. For example, many reviews of marine ecosystem indicators are put into the context of fisheries (e.g., Fulton et al. 2005, Link 2005) and ask the question: Which indicators reflect changes in the population as a result of fishing pressure? The approach we describe throughout this section to select and evaluate indicators for groundfish and ecosystem health could also be applied to the other EBM components.

During reviews of the literature, we identified 125 indicators for the key attributes of the groundfish and ecosystem health components. Indicators of population size are rather obvious, including estimates of abundance in numbers or biomass and estimates of population growth rate. Indicators of population condition vary widely in the literature and are generally dependent on the taxa of interest. Physiological measurements, such as cortisol and vitellogenin levels, and measurements of body growth and size/age structure are often related to the condition of populations via size-related fecundity processes, while measurements of genetic diversity and spatial structure of a population are often cited as measures of resilience in populations against perturbations such as fishing pressure or climate change. Indicators of community composition include community level metrics such as taxonomic diversity and ratios between different foraging guilds. Community composition indicators also include population level trends and conditions across a wide variety of taxa such as marine mammals, seabirds, and zooplankton. Indicators of energetics and material flows primarily examine the base of the food web and the cycling of nutrients that supply the basis for phytoplankton growth.

Evaluation Framework

We follow the evaluation framework established by Levin et al. (2010b). We divide indicator criteria into three categories: primary considerations, data considerations, and other considerations. Ecosystem indicators should do more than simply document the decline or recovery of species or ecosystem health; they must also provide information that is meaningful to resource managers and policy makers (Orians and Policansky 2009). Because indicators serve as the primary vehicle for communicating ecosystem status to stakeholders, resource managers, and policy makers, they may be critical to the policy success of EBM efforts, where policy success can be measured by the relevance of laws, regulations, and governance institutions to ecosystem goals (Olsen 2003). Advances in public policy and improvements in management outcomes are most likely if indicators carry significant ecological information and resonate with the public (Levin et al. 2010a).

Primary considerations

Primary considerations are essential criteria that should be fulfilled by an indicator in order for it to provide scientifically useful information about the status of the ecosystem in relation to the key attribute of the defined goals. They are:

1. Theoretically sound: Scientific, peer-reviewed findings should demonstrate that indicators can act as reliable surrogates for ecosystem attributes.
2. Relevant to management concerns: Indicators should provide information related to specific management goals and strategies.
3. Predictably responsive and sufficiently sensitive to changes in specific ecosystem attributes: Indicators should respond unambiguously to variation in the ecosystem attribute(s) they are intended to measure, in a theoretically or empirically expected direction.
4. Predictably responsive and sufficiently sensitive to changes in specific management actions or pressures: Management actions or other human-induced pressures should cause detectable changes in the indicators, in a theoretically or empirically expected direction, and it should be possible to distinguish the effects of other factors on the response.
5. Linkable to scientifically defined reference points and progress targets: It should be possible to link indicator values to quantitative or qualitative reference points and target reference points, which imply positive progress toward ecosystem goals.

Data considerations

Data considerations relate to the actual measurement of the indicator. Criteria are listed separately to highlight ecosystem indicators that meet all or most of the primary considerations, but for which data are currently unavailable. They are:

1. Concrete and numerical: Indicators should be directly measureable. Quantitative measurements are preferred over qualitative, categorical measurements, which in turn are preferred over expert opinions and professional judgments.
2. Historical data or information available: Indicators should be supported by existing data to facilitate current status evaluation (relative to historic levels) and interpretation of future trends.
3. Operationally simple: The methods for sampling, measuring, processing, and analyzing the indicator data should be technically feasible.
4. Broad spatial coverage: Ideally, data for each indicator should be available across a broad range of the California Current.
5. Continuous time series: Indicators should have been sampled on multiple occasions, preferably without substantial time gaps between sampling.
6. Spatial and temporal variation understood: Diel, seasonal, annual, and decadal variability in the indicators should ideally be understood, as should spatial heterogeneity and patchiness in indicator values.
7. High signal-to-noise ratio: It should be possible to estimate measurement and process uncertainty associated with each indicator, and to ensure that variability in indicator values does not prevent detection of significant changes.

Other considerations

Other considerations are meant to incorporate nonscientific information into the indicator evaluation process. Criteria may be important but not essential for indicator performance. They are:

1. Understood by the public and policy makers: Indicators should be simple to interpret, easy to communicate, and public understanding should be consistent with technical definitions.
2. Historically reported: Indicators already perceived by the public and policy makers as reliable and meaningful should be preferred over novel indicators.
3. Cost-effective: Sampling, measuring, processing, and analyzing the indicator data should make effective use of limited financial resources.
4. Anticipatory or leading indicator: A subset of indicators should signal changes in ecosystem attributes before they occur, ideally with sufficient lead time to allow for a management response.
5. Lagging indicator: Reveals evidence of a failure in or to the attribute.
6. Regionally, nationally, and internationally compatible: Indicators should be comparable to those used in other geographic locations, in order to contextualize ecosystem status and changes in status.

Each indicator was evaluated independently according to these 18 criteria by examining peer-reviewed publications and reports. The result is a matrix of indicators and criteria that contains specific references and notes in each cell, which summarize the literature support for each indicator against the criteria. This matrix can be easily reevaluated and updated as new information becomes available.

Results of Indicator Evaluations

The results of our evaluation of each indicator are summarized in the tables included in this section. Following the framework outlined above, we organized the results of the evaluation by EBM component (i.e., groundfish, salmon, green sturgeon, and ecosystem health).

Evaluation of groundfish indicators

We evaluated a total of 46 indicators of the two key attributes: population size and population condition. In general, the indicators that were evaluated scored well against the primary considerations criteria; however, when indicators performed poorly, it was generally because data were not available at large spatial scales or across long time series.

Population size—We first evaluated three primary indicators that are obvious and well established—numbers of individuals, total biomass of the population, and population growth rate. These indicators performed well across all three evaluation criteria categories and are supported as indicators of population size by all of our primary literature resources (e.g., Fulton et al. 2005, Link 2005, etc.). However, the ability of scientists and managers to measure the abundance or growth rate of any population of groundfish over time relies on surveys that are performed to collect data. Thus we decided to evaluate data sets in the CCLME that measure the abundance or biomass of groundfish populations over time (fishery dependent and fishery independent). This resulted in an evaluation of the strengths and weaknesses of various data sources that estimate the size of groundfish populations. We identified and evaluated a total of 29 potential indicators of population size in the CCLME, summarized in Table 2.

In general, data sources that relied on fishery-dependent data (e.g., commercial landings numbers, total harvest biomass) did not perform well against the primary considerations evaluation criteria. For example, recreational landings data are generally collected at docks and only include individuals and species that are kept by fishers. Thus these data are highly biased by fisher behavior in what species are targeted and what species or individuals they retain. When fishery-independent indicators did not perform well, it was generally because these data sources focused on a very narrow range of species (e.g., hake acoustic surveys) due to gear selectivity (e.g., International Pacific Halibut Commission longline surveys) or because the surveys did not occur at large spatial scales or over long time scales (e.g., NWFSC's hook-and-line surveys, scuba surveys). Interestingly, "local ecological knowledge" scored well in the primary considerations categories, but these interviews of people's memories simply do not exist for most of the CCLME. One attempt in Puget Sound by Beaudreau and Levin (in prep.) has shown a correlation between abundance trends of marine species derived from interviews with fishers and divers and scientifically collected survey data.

Population condition—We identified and evaluated 17 potential indicators (Table 3) for groundfish. Indicators related to age structure, fecundity, or spatial structure of populations generally scored well in the primary considerations categories. Many condition indicators did not score well in the data considerations categories because there is simply little data available across the entire CCLME or data do not exist at multiple periods through time. For example, age at maturity and genetic diversity score high in primary considerations, but there are few examples from a limited number of species in which these data have been collected or processed. Collecting the data (e.g., gonads or fin clips) is relatively easy to do during bottom trawl surveys, but processing the samples can be expensive and taxing for current staff levels.

Evaluation of ecosystem health indicators

We evaluated indicators of the two key attributes: 1) community composition and 2) energetics and material flows. The support in the literature for these indicators varied widely under all evaluation categories.

Community composition—We identified and evaluated 69 potential indicators of overall ecosystem health across a wide variety of taxa and foraging guilds (Table 4). Indicators that scored well under primary considerations generally included species or foraging guild trends and abundance. Many functional group ratios have been identified by modeling exercises as good indicators of diversity and total biomass in the system. A common theme for many indicators was that they performed poorly for the criteria "responds predictably and is sufficiently sensitive to changes in a specific ecosystem attribute." This is because changes in species' or foraging guilds' trends and abundance will influence community composition and ecosystem structure, but changes in community composition may not be reflected in any one species or foraging guild. Moreover, it is conceivable that many of the foraging guild ratio

Table 2. Summary of groundfish population size indicator evaluations. The numerical value under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, California Coastal Oceanic Fisheries Investigative (CalCOFI) egg/larvae abundance reporting has peer-reviewed literature supporting two out of five primary considerations criteria.

Indicator	**Primary consider-ations (5)**	**Data consider-ations (7)**	**Other consider-ations (6)**	**Summary comments**
Biomass	5	7	4	While biomass for each species is an obvious indicator for individual species, aggregate groundfish biomass is not necessarily indicative of the state of the entire groundfish community due to changes in a few large components of the community.
Numbers	5	7	4	Similar comment as for biomass above.
Population growth rate	4	5	5	Theoretically sound and can be calculated at numerous spatial and temporal scales as data sets can be integrated.
Number of groups below management thresholds	3	5	5	Good snapshot of species trends over time, but only 30 of 90 managed groundfish species are assessed.
Stock assessment biomass	5	7	5	Stock assessments perform well for data-rich species. Similar to above, only 30 of 90 groundfish species are assessed.
Bottom trawl survey biomass	5	7	3	Multiple surveys have occurred, but these surveys have been integrated to provide large-scale time series data from 1980 to 2010.
Bottom trawl survey numbers	5	7	3	Multiple surveys have occurred, but these surveys have been integrated to provide large-scale time series data from 1980 to 2010.
Hake acoustic survey biomass	4	5	3	Effective indicator for the most abundant groundfish species in the CCLME, but may not reflect trends of other species. Survey is not reliable when Humboldt squid are present.
Hake acoustic survey numbers	4	0	0	Acoustic surveys generally calculate biomass, not numbers.
Prerecruit survey biomass	3	3	3	The survey provides data on a limited number of species centered around San Francisco.
Prerecruit survey numbers	3	3	3	Similar comment as above.
Hook-and-line survey biomass	5	3	3	Survey is limited in spatial scale, but provides biomass estimates in untrawlable habitats in the Channel Islands, California.
Hook-and-line survey numbers	5	3	3	Similar comment as above.
PISCO scuba surveys biomass	5	0	0	Scuba surveys do not provide actual data on biomass.
PISCO scuba surveys numbers	5	4	3	Scuba surveys are limited in spatial scale and highly variable for cryptic species.

Table 2 continued. Summary of groundfish population size indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, CalCOFI egg/larvae abundance reporting has peer-reviewed literature supporting two out of five primary considerations criteria.

Indicator	**Primary considerations (5)**	**Data considerations (7)**	**Other considerations (6)**	**Summary comments**
National Park Service kelp monitoring survey biomass	5	0	0	Similar comment as for PISCO scuba surveys biomass above.
National Park Service kelp monitoring survey numbers	5	4	3	Similar comment as for PISCO scuba surveys numbers above.
IPHC longline survey biomass	4	2	3	International Pacific Halibut Commission (IPHC) longline surveys are useful for a small number of species.
IPHC longline survey numbers	4	2	3	Similar comment as above.
CalCOFI egg/larvae abundance	2	3	3	Survey is most effective for coastal pelagic species. The survey does not collect enough information on most groundfish species. In addition, species identification of larval rockfish requires DNA techniques.
Pot surveys biomass	1	1	3	Variation in behavior of fish biases these passive survey methods. Survey no longer occurs.
Pot surveys numbers	1	1	3	Similar comment as above.
Commercial landings biomass	1	3	1	Fishery-dependent data biased toward fisher behavior, fleet dynamics, and management restrictions. Only economically valuable species.
Commercial landings numbers	1	2	1	Similar comment as above.
Recreational landings biomass	1	3	1	Similar comment as above.
Recreational landings numbers	1	3	1	Similar comment as above.
Total harvest biomass, catch per unit effort	1	4	1	Similar comment as above.
Bycatch abundance	0	5	4	Levels of bycatch are heavily influenced by fisher behavior and management restrictions.
Local ecological knowledge	4	1	4	Theoretically sound, but limited data throughout the CCLME.

Table 3. Summary of groundfish population condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Cortisol/vitellogenin has peer-reviewed literature supporting two out of five primary considerations criteria.

Indicator	**Primary considerations (5)**	**Data considerations (7)**	**Other considerations (6)**	**Summary comments**
Age structure of populations	5	7	4	Strongly supported by the literature in most criteria.
Size structure of populations	0	5	4	Size structure from catch data generally biased by gear selectivity and catchability.
Center of distribution (latitudinal or depth changes)	2	5	5	Distributional shifts tend to suggest a pressure is acting on the population (i.e., fishing or climate).
Genetic diversity of populations	5	2	2	Scores well in primary considerations, but there is an overall lack of data for most groundfish species at multiple points in time.
Age at maturity	5	1	3	Similar comment as above.
Size at maturity	3	2	2	Similar comment as above.
Diet of groundfish	0	1	1	Prey is highly variable and there are few species with enough data over time and space to understand differences.
Larval abundance	2	3	2	Abundance of larvae most likely driven by oceanographic conditions and may not be reflective of the condition of specific populations.
Parasitic load	3	1	0	Theoretically sound, but little data for most species.
Condition factor (K)	3	5	2	Theoretically sound as condition of fish is directly related to growth and fecundity, but this is generally not described—data limited to species which have both individual length and weight measured during surveys.
Cortisol/vitellogenin	2	1	1	May be related to condition, but changes in the attribute are not likely to vary with this indicator at any scale but the very smallest.
Disease (liver and gall bladder)	2	1	1	Similar comment as above.
Fecundity	5	1	2	Scores well in primary considerations, but there is an overall lack of data available for most species across time and space.
Body growth	2	5	5	Typically, age is calculated from otoliths collected during bottom trawl surveys, but growth could also be measured with these samples.
Spatial structure of population	5	5	4	Theoretically sound and data are available for many species, but stocks are generally assessed at the scale of the entire coast.
Mean length of species	5	1	5	Lengths measured for many species, but there may be limited data on unassessed species.
Rebuilding timeline	3	7	5	Available for overfished species. Most species stop declining, but some have not increased.

Table 4. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	**Indicator**	**Primary consider-ations (5)**	**Data consider-ations (7)**	**Other consider-ations (6)**	**Summary comments**
Marine mammals	Cetacean species status and trends	3	2	3	Theoretically sound sentinel species, but high variability in data; low sample size and numerous coverage gaps; slow population response rate.
	Pinniped abundance and population trends	3	4	3	See above, although surveys at breeding grounds and haul-out sites facilitate population estimates.
	Pinniped biomass	3	4	2	See above.
	Pinniped annual reproductive performance	4	4	4	Strong link to nutritional stress, contaminants, and disease; incomplete pup counts for some species, but long time series for others.
	Pinniped contaminant load	3	3	2	Theoretically sound, but problems due to high migratory patterns, limited spatial and temporal replication, high analysis costs, and lagged response.
	Pinniped diet (fatty acids, stable isotopes)	2	4	2	Reflects broad status of food supply, variety of methods can discern variable scales of feeding, high sampling replication and effort required.
	Pinniped stress hormones	0	2	1	Integrative measure of stress, but difficult to differentiate cause and effect; baseline information needed to discern normal variation, data generally lacking across species' ranges.
	Pinniped disease, death, mortality, bycatch	2	4	4	Theoretically valid and increasingly well studied; often difficult to attribute cause to changes in pinniped mortalities; mortality database maintained by the U.S. Geological Survey's National Wildlife Health Center since 1971.
	Integrative marine mammal index (multivariate)	2	1	3	Can be used to show predictable responses to stressors, type of data in the index affect interpretability, unlikely to correlate specific cause with effect, data requirements high.
Key fish groups	Forage fish biomass; species status and trends	3	0	5	Changes in a single group may or may not be indicative of entire community. Most forage fish data are fishery dependent but new surveys are coming on-line.
	Groundfish status and trends	3	7	5	Similar to comment above except that ample data are available for species and individuals susceptible to bottom trawling.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	**Indicator**	**Primary consider-ations (5)**	**Data consider-ations (7)**	**Other consider-ations (6)**	**Summary comments**
Key fish groups (cont.)	Flatfish biomass	3	7	5	Changes in a single group may or may not be indicative of the entire community. Ample data are available for species and individuals susceptible to bottom trawling.
	Zooplanktivorous fish biomass	3	0	5	Identified as the best indicator of total biomass in marine systems during modeling exercises, but data for many species will be limited (see forage fish biomass).
	Piscivorous fish biomass	3	1	5	Changes in a single group may or may not be indicative of the entire community. Data for many species may be limited to fishery-dependent data.
	Roundfish biomass	3	7	5	Identified as a significant indicator for nine ecosystem attributes in modeling exercises.
	Demersal fish biomass	3	7	5	Changes in a single group may or may not be indicative of the entire community, but data are generally available.
	Pelagic fish biomass	3	0	5	Changes may indicate predatory release of prey populations or insufficient forage base, but changes in a single group may not be indicative of the entire community.
	Rockfish biomass	3	7	5	Changes in a single group may or may not be indicative of the entire community, but data are available for many rockfish species.
	Juvenile rockfish index	3	6	4	Can be useful in forecasting year-class strength and reflect trends in adult biomass, used frequently in stock recruitment models, historical but spatially limited data available for CCLME.
	Juvenile hake abundance	3	6	4	See juvenile rockfish abundance above.
Salmon	Salmon smolt-to-adult survival rate	5	7	2	Related to dominant modes acting over the coastal region, extensive historical records, perhaps best as a retrospective (lagging) indicator of historic ocean conditions.
	Salmon adult escapement	3	5	3	Highly influenced by ocean conditions; large extensive historic database, but difficult to discern cause and effect; lagging indicator.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	Indicator	Primary consider-ations (5)	Data consider-ations (7)	Other consider-ations (6)	Summary comments
Seabirds	Marine seabird species status and trends	2	3	3	Easily enumerated top consumers, difficult to attribute change to particular causes, often respond to environmental change or management actions, better indicator at years to decades.
	Seabird biomass	2	4	2	Primarily used in food web models, not highly sensitive, changes likely occur at same rate as populations, few locations where this is monitored.
	Seabird annual reproductive performance	4	5	4	Strong correlation between breeding success, food availability, and large scale indices of ocean climate; expensive and time consuming; long-term data sets available along Pacific coast.
	Seabird contaminant load	0	4	1	See pinniped contaminant load above.
	Seabird diet (fatty acids, stable isotopes)	4	2	2	See pinniped diet above.
	Seabird stress hormones	0	2	1	See pinniped stress hormones above.
	Seabird disease, death, mortality, bycatch	2	5	5	See pinniped disease, death, mortality, bycatch above.
	Integrative seabird index (multivariate)	2	2	3	See integrative marine mammal index above.
	Marine shorebird species status and trends	2	3	2	Provide information on coastal and shoreline habitat; often slow to respond to environmental change or management actions, but difficult to attribute cause and effect; some monitoring data available, but unpublished.
Reptiles	Sea turtle status and trends	2	1	3	Widely dispersed, nonprominent member of CCLME; difficult to monitor population trends, except adult females during nesting events; slow to respond to environmental change or management actions, and attribute cause and effect; limited spatial extent.
Shellfish and invertebrates	Jellyfish biomass, status and trends	4	3	2	Indicator of trophic energy transfer and pelagic community composition, abundance can be linked to human activities, no existing reference condition, historical data in CCLME are limited, no evidence to suggest as leading indicator.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	Indicator	Primary consider-ations (5)	Data consider-ations (7)	Other consider-ations (6)	Summary comments
Shellfish and invertebrates (cont.)	Squid, Humboldt	1	2	2	Range expansion correlated with reduction in top predators; possibly indicates shifts in climate regimes, ocean circulation, and ecosystem-wide food webs; data minimal and of limited spatial and temporal scale.
	Crustaceans: catch and survey trends; larval surveys	4	5	4	Attributed to climate induced changes in water column temperature and fishing; indicative of community regime shift (high trophic level groundfish to low trophic level crustaceans); zooplankton data sets provide good record of larval abundance for estimating spawning stocks.
	Coastal oyster condition index				Incomplete.
	Shellfish status, trends				Incomplete.
	Benthic invertebrate biomass	4	2	2	Correlates well with ecosystem health and responds to fishing pressure; some databases available, although depth strata and sampling design not readily apparent; gradual change should show major community reorganization.
Zooplankton	Zooplankton abundance and biomass	4	7	5	Base of food web, fundamental component of CCLME, correlated with regime shift and climate change, can be used to estimate thresholds, several ongoing long-term data sets.
	Copepod species ratio (cold vs. warm) or zooplankton species biomass anomalies)	5	7	5	Reflect modifications in water masses, currents, or atmospheric forcing; respond rapidly to climate variability; some taxa reflect influence of different water types on ecosystem structure; data availability as above.
	Euphausid biomass and richness	5	2	3	Indicator of plankton biomass changes, critical link in marine food web, low counts and high patchiness in samples may increase variability, data availability as above.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	Indicator	Primary considerations (5)	Data considerations (7)	Other considerations (6)	Summary comments
Diversity indices	Biodiversity index (Hurlbert’s delta)	4	7	3	Reflects taxonomic evenness; calculated from abundance estimates; change detectable with latitude and depth at large scales; natural and baseline levels of evenness may vary; significance of certain types of change not known; data available from groundfish, zooplankton, and benthic invertebrate surveys.
	Slope of log (biomass) vs. trophic level–Simpson Diversity Index	4	6	1	Theoretically sound, calculated from abundance estimates; difficulty linking diversity indices to targets or reference points; for data availability see Hurlbert’s biodiversity index above.
	Marine mammal diversity–Shannon Diversity	4	5	2	Measures taxonomic richness and evenness, community stability related to higher diversity, difficulty linking diversity indices to targets or reference points, for data availability see Hurlbert’s biodiversity index above.
	Adult sablefish biomass (indicator of diversity)–Shannon Diversity	4	7	4	Theoretically correlated with community diversity in British Columbia ecosystem during modeling exercises; for data availability, see groundfish biomass trends and stock assessments above.
	Detritivore biomass (indicator of diversity)–Shannon Diversity	4	3	1	See above; for data availability, see benthic invertebrate population trends above.
	Taxonomic distinctness (average and variation in)	3	6	3	Uses species lists, not abundance data; minimal data requirements allows integration of data sets, use of historical data, and data of varying quality; for data availability see Hurlbert’s biodiversity index above.
	Number of threatened species (IUCN A1 criteria as modified by Dulvy et al. 2006)	4	7	3	Composite indicator based on weighted average of species threat, criteria somewhat arbitrary, linking index to targets or reference points is difficult, data available and numerical.
Functional groups	Top predator biomass (trophic level > 4.0)	5	2	4	Top predator removal typically results in trophic cascades. Data available for many groundfish and seabird top predators, but data for sharks and marine mammals are less reliable.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	Indicator	Primary consider-ations (5)	Data consider-ations (7)	Other consider-ations (6)	Summary comments
Functional groups (cont.)	Invertivore biomass	2	7	2	Correlated with several measures of diversity and total biomass in modeling exercises, but variation in community composition may not be detected by variation in this functional group alone.
	Detritivore biomass	3	7	2	Similar comment as above.
	Herbivore biomass	3	7	2	Similar comment as above.
	Scavenger biomass	4	7	2	Some evidence that disturbances, such as fishing activities, induce chronic increases in scavenger populations, but changes in this one functional group may (or may not) be indicative of the entire community.
Functional group ratios	Forage fish and jellyfish biomass ratio	3	2	1	Highly correlated with diversity measures and mean trophic level in modeling exercises. Data limited for both groups and ratios of functional groups are not easily understood indicators.
	Piscivorous and Zooplanktivorous fish biomass ratio	3	0	2	Highly correlated with diversity measures in modeling exercises, but how many species have data available is unknown.
	Pelagic and demersal fish biomass ratio	3	1	2	Appears to be a proxy for differential impact of nutrients on the pelagic and benthic food webs based on modeling exercises.
	Zooplankton and phytoplankton biomass ratio	2	1	1	Highly correlated with measures of diversity and mean trophic level in modeling exercises, but data are particularly limited for phytoplankton, although proxies such as chl *a* have been used.
	Rockfish and flatfish biomass ratio	2	7	1	Highly correlated with measures of diversity and total biomass in modeling exercises.
	Invertivore and herbivore biomass ratio	3	7	1	Similar to comment above.
	Finfish and crustacean biomass ratio	3	7	1	Indicative of community regime shift in several systems from high trophic level groundfish to a low trophic level, crustacean-dominated system; see comments above under crustacean and groundfish biomass and survey trends for data availability.
Fishery catch	Trophic level of catch (mean biomass)	2	1	1	Shortcomings associated with typical catch-based data; size-based indicators are better because they do not require diet data, are less error prone, and more easily collected.

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

Guild	**Indicator**	**Primary consider-ations (5)**	**Data consider-ations (7)**	**Other consider-ations (6)**	**Summary comments**
Fishery catch (cont.)	Proportion noncommercial species (unfished groups)	5	4	3	Modeling results show response to variation in fishing pressure and correlation with ecosystem attributes, one of the more sensitive indicators of changes in species composition.
	Total catch and landings of target species	1	4	2	Considered good indicator of fishing effects but poor indicator of marine ecosystem performance, primarily a function of fishing effort and a poor approximation of production, landings can be misleading in assessments ecosystems.
	Total fishery removals of all species (including bycatch)	1	3	2	See above, bycatch data often not recorded.
	Total fishery removals of all species	2	6	3	See above.
	Mean length, all species	4	1	5	Useful and simple indicator to evaluate effects of fishery removals, but may not be observable over short-term monitoring data sets.
	Slope size spectrum, all species	2	1	2	Good indicator of fishing effects, models show change is predictable and consistent, unclear what attributes it would act as an indicator for besides general ecosystem health, thresholds unclear, size data sparse for some species.
Habitat species	Kelp forest coverage	4	5	5	Kelp forests occur at small scales compared to the entire California Current, so overall ecosystem structure may not be tied to kelp coverage, but these are important habitats for recruitment of important species.
	Area of live, hard coral	4	2	2	Similar comment as above. Data on spatial extent of coral cover are limited.

indicators (e.g., piscivorous to zooplanktivorous fish ratio) could have scientifically defined reference points and progress targets, but these ratios may not be easily understood by the public and policy makers for establishing management targets. These evaluations suggest that multivariate indicators may be more indicative of changes in ecosystem structure. Changes in many of these community-level metrics cannot be observed in short-term monitoring sets and may be more useful at longer management time scales (Nicholson and Jennings 2004).

Population trends of large-bodied, long-lived, or high trophic–level vertebrates (e.g., cetaceans, pinnipeds, sea turtles, or seabirds) were consistently considered poor indicators of ecosystem condition because of the inherent low variability of their life history characteristics, which limited their ability to serve as an early warning (i.e., leading indicator) of impacts, as well as the associated difficulty in attributing change to particular causes or interpreting the spatial extent of trends (Hilty and Merenlender 2000, Holmes et al. 2007). Indicators related to fishery removal (e.g., total catch or total harvested biomass) also performed poorly because landings were often poorly correlated with marine population trends due to fleet behavior and dynamics, targeting and behavior of the fishermen, and bias from misreporting (Hilborn and Walters 1992, Watson and Pauly 2001, Rochet and Trenkel 2003, de Mutsert et al. 2008).

Energetics and material flows—We identified and evaluated 10 potential indicators for the CCLME (Table 5). In general, there was wide disparity between indicators that met both primary and data considerations and those that did not. Most indicators that were theoretically sound, relevant to management, and predictably responsive tended to meet many of our data criteria (e.g., chlorophyll *a* [chl *a*], inorganic nutrient levels), whereas those that did not meet many of the primary criteria also fell short with regard to data considerations (e.g., oxidation rates, respiration rates). Exceptions to this rule included indicators that were: 1) not necessarily well characterized or understood in ocean upwelling systems (e.g., nitrogen fixation rates), 2) difficult to measure directly due to methodological difficulties (e.g., microbial decomposition rates), or 3) recognized as important but poorly characterized by data sets at large spatial scales or over long time series (e.g., phytoplankton biomass and particulate organic matter [POM] levels).

Inorganic nutrient levels and proxies for primary productivity such as chl *a* concentration are the most widely available indicators for energy and material flows in the California Current. Remote-sensing data are a valuable source of this information, though other, labor-intensive approaches are available for obtaining spatially explicit and finely resolved understanding of primary productivity as well (e.g., plankton tows). Biogeochemical approaches for measuring carbon cycling rates are well developed and theoretically sound, but such data are not widely available and can be quite expensive to obtain. Modeling efforts (e.g., Ecopath with Ecosim) currently provide a useful tool for estimating the magnitude of secondary production and pathways of energy flows and carbon cycling throughout the food web, but more detailed data collection is needed to validate many of the inherent model assumptions. Making up for this deficiency will require detailed, broad-scale studies of how different species interact with the physical and chemical oceanography of the CCLME to affect processes such as nitrogen fixation, carbon sequestration, and microbial decomposition. Nevertheless, we suggest the evaluation of additional indicators of energy and material flows in the future.

Table 5. Summary of ecosystem health: Energetics and material flows indicator evaluations. The numerical value under each consideration represents the number of evaluation criteria supported by peer-reviewed literature. For example, microbial decomposition/respiration rate has peer-reviewed literature supporting two out of five primary considerations criteria.

Indicator	**Primary considerations (5)**	**Data considerations (7)**	**Other considerations (6)**	**Summary comments**
Phytoplankton biomass	4	1	2	Good indicator of pelagic ecosystems and hydroclimatic forcing, few long-term time series that identify phytoplankton species.
Chl a	4	5	3	Good indicator of phytoplankton biomass and amount of energy fueling the ecosystem, satellite remotely sensed chlorophyll concentration data available system wide.
Nitrogen fixation rate, nitrification/denitrification rate, ^{15}N ratios	1	3	0	May indicate vigor or resilience of an ecosystem, although the CCLME is an upwelling system characterized by nutrient limitation; scientific understanding of ocean N fixation lacking.
Inorganic nutrient levels: dissolved inorganic nitrogen, silicate, phosphate, iron	4	3	5	Strongly linked to upwelling events, which drive system productivity and control production; poorly characterized in space and time, except intensive sampling at individual regions.
Stratification: temperature, salinity; thermocline depth	0	0	0	Thought to limit nutrient exchange and be source of decadal regime shift, little evidence in scientific literature that it acts as good indicator.
Oxidation rate	0	0	0	Little evidence in scientific literature that oxidation rates act as good ecosystem indicator.
Microbial decomposition/ respiration rate	2	0	1	Good indicator of ecosystem stress; however, not routinely measured directly; very limited global database (<1,700 samples); most measurements from shallow, euphotic zone during spring.
Respiration rate	2	1	1	Captures the overall state or maturity of an ecosystem, although too few samples collected worldwide to determine spatial and temporal variability; methods have precision limitations.
Number of cycles (carbon)	5	5	3	Carbon cycling decreases as ecosystem stress increases, can be estimated using mass balance models.
POM, dissolved organic carbon	0	3	0	Little evidence in scientific literature that POM acts as good ecosystem indicator; however, high POM usually linked to hypoxia and dead zones; poorly characterized in CCLME.

Scoring Indicators

The matrix of ecosystem indicators and indicator evaluation criteria provides the basis for scoring the relative support in the literature for each indicator (Levin et al. 2010b). For each cell in the evaluation matrix, we assigned a literature-support value of 1.0, 0.5, or 0.0 depending on whether there was support in the literature for the indicator, the literature was ambiguous, or there was no support in the literature for the indicator, respectively. However, scoring indicators also requires careful consideration of the relative importance of evaluation criteria. The importance of the criteria will certainly vary depending on the context within which the indicators are used and the people using them. Thus scoring requires that managers and scientists work together to weight criteria. Failure to weight criteria is, of course, a decision to weight all criteria equally.

To determine the weightings for each of the evaluation criteria, we asked 15 regional resource managers, policy analysts, and scientists to rate how important each of the evaluation criteria was to them. Approximately one-third of the responses came from each profession category. We asked each person to indicate how strongly they agree or disagree with the following statement about each of the evaluation criteria: "I feel this criterion is of high importance when ranking indicators for use in the California Current IEA." Each person then assigned one of the following ratings to each criterion: strongly disagree, disagree, neutral, agree, or strongly agree. Each rating was assigned a value between 0 and 1, where strongly disagree equals 0, disagree equals 0.25, neutral equals 0.5, agree equals 0.75, and strongly agree equals 1.0. We then calculated the percentage of responses for each rating for each criterion. The percentages were multiplied by the assigned value for each rating, then summed across each criterion and divided by 100. This provided an average weighting for each criterion (Table 6). We used the distribution of average weightings and calculated the quartiles for this distribution. We assigned each criterion to the quartile into which its average fell. For example, the average weighting for "historically reported" (under the other considerations category) was 0.39 and that value was in the lowest quartile of the distribution, so this criterion received a weighting of 0.25.

For each cell, the literature-support value was multiplied by the weighting for the respective criterion, then summed across each indicator. This score was used as the final score for each indicator. For each key attribute of each EBM component, we calculated the quartiles for the distribution of scores for each indicator. Indicators that scored in the top quartile (top 25%) for each attribute of each goal were considered to have good support in the literature as an indicator of the attribute they were evaluated against. We describe below the results of the evaluation for each indicator that scored in the top quartile.

Indicators that Scored in the Top Quartile

Groundfish

Population size—*Stock assessment biomass*. Stock assessment trends in spawning stock biomass are well established measures of the size of the many commercially important species and are subject to intense peer review. Assessments are tied directly to management efforts and provide quota levels for various fisheries. Changes in assessed populations reflect changes in the abundance of individuals collected in bottom trawl surveys. When management restrictions are

Table 6. Assignment of weightings to each criterion. Fifteen regional resource managers, policy analysts, and scientists were asked to indicate how strongly they agreed or disagreed with the following statement: "I feel this criterion is of high importance when ranking indicators for use in the California Current IEA." Values under each rating are the percentage of responses in favor of each. Weightings were averaged and each criterion assigned to the quartile in which its average weighting fell in the distribution.

Evaluation criteria	**Strongly disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	**Average weighting**	**Quartile of average weighting**
Historically reported	6.7	40.0	47.0	6.7	0	0.39	0.25
Operationally simple	0.0	13.3	40.0	20.0	13	0.51	0.25
Regionally, nationally, and internationally compatible	0.0	13.0	67.0	20.0	0	0.52	0.25
Theoretically sound	0.0	0.0	13.3	40.0	20	0.57	0.50
Anticipatory or leading indicator	0.0	13.3	46.7	40.0	0	0.57	0.50
Relevant to management concerns	0.0	0.0	0.0	40.0	30	0.60	0.50
Responds predictably and is sufficiently sensitive to changes in specific ecosystem attributes	0.0	0.0	20.0	33.0	27	0.62	0.50
Continuous time series	0.0	6.7	47.0	33.3	13	0.63	0.50
Numerical	0.0	13.3	47.0	13.3	27	0.64	0.50
Broad spatial coverage	0.0	0.0	53.0	33.3	13	0.64	0.50
Responds predictably and is sufficiently sensitive to changes in specific management actions or pressures	0.0	6.7	13.3	60.0	13	0.66	0.75
Cost-effective	6.7	0.0	33.0	40.0	20	0.67	0.75
Spatial and temporal variation understood	0.0	0.0	27.0	73.3	0	0.68	0.75
High signal-to-noise ratio	0.0	13.3	33.0	13.3	40	0.70	0.75
Concrete	0.0	0.0	33.3	40.0	27	0.74	0.75
Understood by the public and policy makers	0.0	13.3	7.0	53.3	27	0.74	0.75
Historical data or information available	0.0	0.0	6.7	80.0	13	0.76	1.00
Linkable to scientifically defined reference points and progress targets	0.0	6.7	13.3	60.0	27	0.80	1.00

established, assessed populations generally stop declining. Many species begin to recover and experience population growth according to the assessments, but there are other species which appear to respond slowly to management actions (see Miller et al. 2009). Assessments provide two primary reference points for assessed species: B40 and B25. B40 is the level of spawning stock biomass at which stocks are considered at their optimal yield—40% of virgin spawning biomass. B25 is the level of spawning stock biomass at which stocks are overfished—25% of virgin spawning biomass. However, only 30 of 90-plus species within the Pacific Coast Groundfish Fishery Management Plan (PCGFMP) have been assessed and there are generally 200–300 species of fish detected each year in the West Coast Groundfish Trawl Survey (WCGTS) (e.g., Keller et al. 2008).

Stock assessments use data from multiple sources for various species, but the primary source of data is from the WCGTS. This survey contains data from the Alaska Fisheries Science Center's (AFSC) triennial bottom trawl survey from 1977 to 2004 and the Northwest Fisheries Science Center (NWFSC) annual bottom trawl survey from 1998 to 2010. These surveys have covered different spatial extents in the past, but the current survey is a random-stratified design by depth which samples across the entire U.S. West Coast from 50 to 1,280 m (Figure 3). Assessments use multiple data sources incorporating length frequencies, diet, age structure, and fecundity measures when available. Analyses used to generate time series data generally use the same stock assessment framework (Stock Synthesis version 3 in 2009, e.g., Stewart 2009). Assessments generally use multiple data sources across the range of each stock (e.g., Gertseva et al. 2009, Stewart et al. 2009); however, some species (i.e., cabezon [*Scorpaenichthys marmoratus*] and bocaccio [*Sebastes paucispinis*]) are only assessed in specific regions along the West Coast (Cope and Key 2009, Field et al. 2009).

The major findings of a stock assessment can be easily understood by the public and policy makers (i.e., these species are declining, these species are increasing, these species are overfished). Assessments are typically done on species that are worse off, thus assessments generally show declines that have already happened. Since assessments measure spawning biomass, it is generally an assessment of processes that have already taken place (i.e., spawning stocks in the past were fished or had bad years and now the current spawning biomass reflects those bad years), so this is generally a lagging indicator.

Bottom trawl survey biomass. The WCGTS is well established and has been developed with input by stock assessment scientists and through outside peer review during the PFMC process. The major objective of this survey is to provide fishery-independent data necessary to conduct formal stock assessments of fish species managed within the PCGFMP (e.g., Keller et al. 2008). Historically, this survey was performed triennially by the AFSC from 1977 to 2004. In its current format, the WCGTS survey has been conducted annually since 2003 by the NWFSC. Data are collected in trawlable habitats from the U.S.-Canada border to the U.S.-Mexico border between the months of May to October. Each trawl is 15 minutes in duration and total counts and aggregate weights by species are recorded for all species. Subsamples of targeted species (generally consisting of the 90 managed species) are randomly selected for individual measurements of length and weight, removal of age structures, and sex determination. In a typical year, approximately 600 trawls are successfully conducted, approximately 150,000 fish are individually measured for weight and length, and more than 20,000 have otoliths removed for aging (i.e., Keller et al. 2008). Other individuals are sampled for genetics, stomach

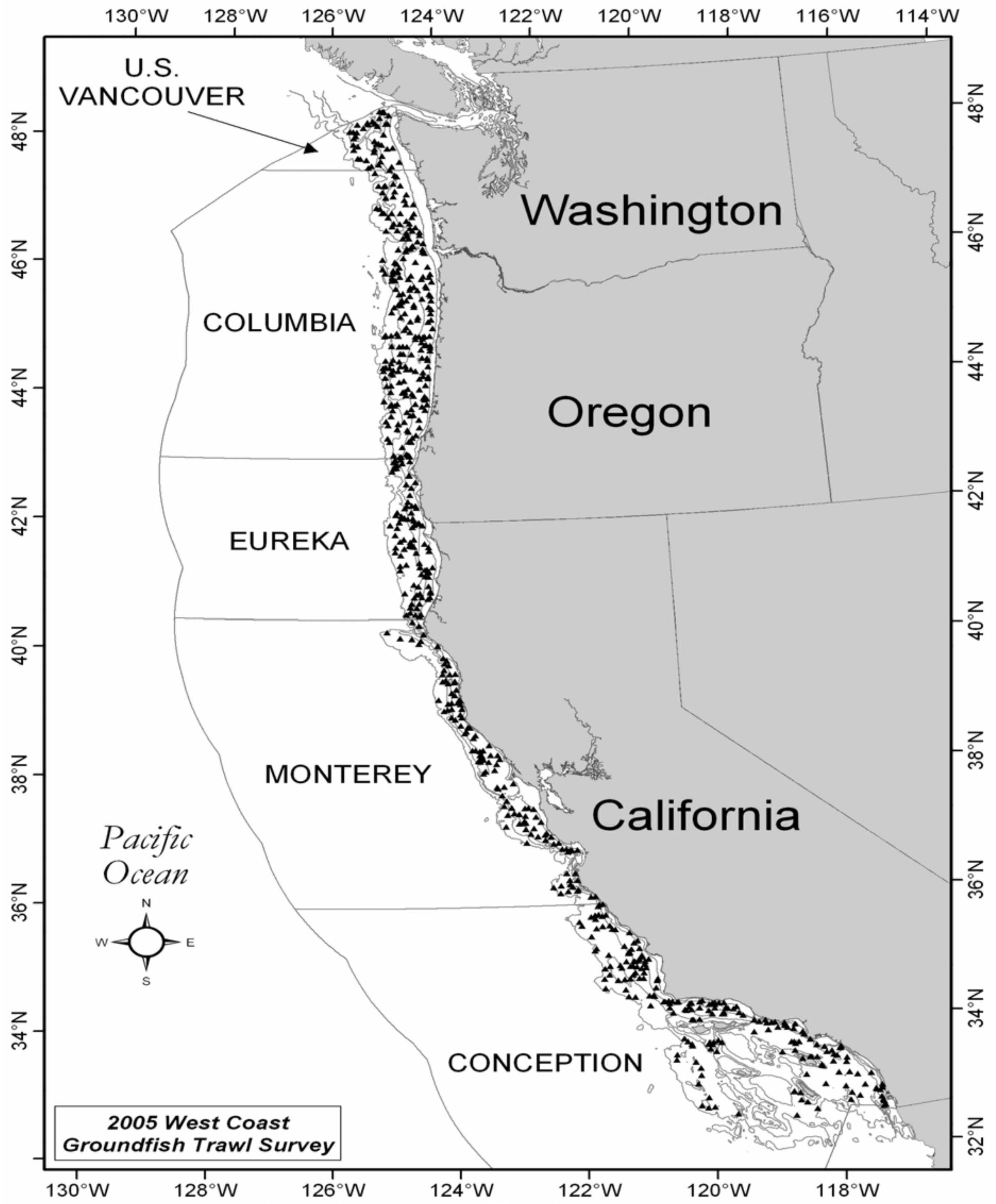

Figure 3. Example of the number and spatial extent of locations (triangles) surveyed by the West Coast groundfish trawl survey each year during 2003–2010. (Reprinted from Keller et al. 2008.)

contents, maturity level, and toxicology as special projects. These data are in a Fishery Resource Analysis and Monitoring Division database at NWFSC.

These data allow for estimates of density and biomass and evaluation of change in population size for many more species than are assessed through formal stock assessments (e.g., Levin et al. 2006). As noted, only 30 of the 90-plus managed species on the U.S. West Coast are formally assessed, while there are approximately 250 species or groups of fish detected each year during the WCGTS. One caveat to the bottom trawl survey is data will always be biased towards species that occupy trawlable habitats in depths 50–1,280 m and towards life history stages susceptible to the survey's trawl gear. Most small individuals, either young individuals or smaller species, are not captured by the bottom trawl survey because they are in shallower water as juveniles or they escape through the net mesh. Moreover, species that move into rockier and untrawlable habitats through life are not sampled at larger sizes in the bottom trawl survey. The bottom trawl survey is also not a good indicator of Pacific hake biomass, which is a more pelagic species and comprises the largest component of the groundfish population in the CCLME from a fisheries standpoint (Miller et al. 2009).

Estimates of biomass calculated from trawl surveys are easily understood by the public and have been used historically by policy makers for regulatory and legislative purposes. The estimates of abundance from the trawl survey are concurrent with the current abundance of the stock, but these estimates are a lagging indicator of what was happening to the stock several years ago (i.e., what were the conditions of the ecosystem that allowed recruitment to be good or bad, as many species aren't captured in the survey until they are 5–8 years old). Trawl surveys performed appropriately are compatible with other regional, national, or international surveys.

Biomass. Biomass is a standard measurement of population size and is cited voluminously in the indicator literature (e.g., Link et al. 2002, Fulton et al. 2005). Biomass is the metric calculated in formal stock assessments and the metric used for harvest rates of individual species in West Coast fisheries. However, an aggregate groundfish biomass is not necessarily indicative of the state of the groundfish community, because this information will be biased towards a few large components of the community. For example, Pacific hake is the most abundant groundfish species detected in the WCGTS and variation in this species will likely swamp detectable variation in the rest of the groundfish community. Thus any indicator of population size will need to identify species of interest or representatives of different functional groups to monitor changes over time. Alternatively, multivariate measurements of the groundfish community will need to be developed to detect meaningful changes in the population size of groundfish.

Population growth rate. Population growth rate is a standard metric for measuring changes in population size over time (e.g., Levin et al. 2006) and is a common metric in the indicator literature (Sibly and Hone 2002, Trenkel and Rochet 2003, Fulton et al. 2005). Population growth rate is not explicitly stated in formal stock assessments, but the metric is shown as spawning stock biomass over time. The growth rate of a population integrates the size of the spawning stock and the variability in recruitment of young fish. In many cases, population growth rate will increase with increases in spawning stock, but if recruitment is density independent or is limited by environmental conditions, this relationship will not hold true (Hilborn and Walters 1992). Sibly and Hone (2002) argue that "population growth rate is the key unifying variable linking the various facets of population ecology. The importance of population growth rate lies partly in its central role in forecasting future population trends; indeed if the form of density dependence were constant and known, then the future population dynamics could to some degree be predicted."

Data for calculating population growth rates for many groundfish species are available via the WCGTS. It is unknown at this point how many species have enough data to make this calculation. As an indicator, population growth rate will always be lagging due to timing of data availability and calculation of the indicator. Because most species are not collected by conventional trawl surveys until they are 5 to 8 years old, the most recent estimates of population growth will be measures of the environmental conditions since these individuals were born. Moreover, predictions from the model of population growth may suggest a trend, but environmental variation will always alter this prediction (Hilborn and Walters 1992).

Population growth rate is easily understood by the public and policy makers; species are increasing, decreasing, or remain constant. In the form of spawning stock biomass, this indicator has been used historically and is compatible with measurements of population size from other regions and nations.

Hake acoustic survey biomass. The Pacific hake integrated acoustic and trawl survey has been conducted since 1977 to assess the size and distribution of the population in the CCLME (Helser and Martell 2007, Helser et al. 2008). The joint survey between the United States and Canada has taken place in 1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998, 2001, 2003, 2005, 2007, and 2009. The survey is generally conducted between June and August along the continental slope and shelf from Monterey, California (lat 35.7°N), to the Dixon Entrance in northern British Columbia (lat 54.8°N). During the survey, hydroacoustics are used to measure numbers (or biomass) and subsequent midwater trawls over the same location are used to collect length and age compositions.

This survey is a single species survey that does not provide adequate information for other groundfish species. In addition, massive northward movements of Humboldt squid (*Dosidicus gigas*) complicated the 2009 survey. Since it is very difficult to distinguish between Pacific hake and Humboldt squid with the current acoustic survey methodologies, changes in the spatial distribution and frequency of occurrence of Humboldt squid in the survey area may pose problems in the future.

Similar to the bottom trawl surveys, the acoustic survey produces data that are easily understood by the public, have been used historically, and are compatible with measurements used by other regions and nations.

Number of groups below management thresholds. A simple indicator of the status of assessed groundfish species is the number of species that are currently below various management thresholds. The Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) requires fishery conservation and management measures that prevent overfishing, while achieving optimum yield on a continuing basis (16 U.S.C. §1851a1). Overfishing occurs when the actual catch of a species exceeds the allowable catch for that species. The MSFCMA also requires that fishery management plans specify objective and measureable criteria for identifying when a fishery is overfished and contain conservation and management measures to prevent or end overfishing and rebuild the fishery (16 U.S.C. §1853a10). Under the PCGFMP, a species (or stock) is considered overfished when its current spawning stock biomass is assessed to be less than 25% of unfished spawning biomass. NMFS's national standard guidelines clarify that "overfished" relates to biomass of a stock or stock complex, while "overfishing" pertains to a rate or level of removal from a stock or stock complex (50 CFR 600.310(e)(2)). Estimates of spawning stock biomass and virgin biomass are calculated during the formal stock assessment analysis.

Data to measure the overfishing threshold is available for all stocks that have an identified allowable catch. Approximately 30 of the 90-plus managed groundfish species can be evaluated for the overfished threshold. However, data are likely available from the WCGTS to evaluate this threshold for other species.

The public can easily understand whether a species is above or below specific management thresholds and policy makers have used this indicator for regulatory and legislative purposes. Other nations have similar thresholds in their management frameworks (Gray et al. 2010).

Population condition—*Age structure of populations.* The longevity of many groundfish species allows them to allocate their reproductive output across many years. This strategy is particularly important when environmental conditions are unfavorable for survival of larvae or new recruits (Leaman and Beamish 1984, Berkeley et al. 2004a). In addition, there is growing support in the literature that older fish produce more fit eggs and larvae (Hislop 1988, Berkeley et al. 2004a, Wright and Gibb 2005, Sogard et al. 2008). This work suggests that older individuals may produce offspring that will survive and recruit to the population in higher proportions than offspring from younger individuals. This would be particularly true during years when environmental conditions were less than optimal. Thus populations with a truncated age structure (fewer older individuals) may have more difficulty sustaining current population levels. For many groundfish species, the largest and oldest individuals have been historically targeted and removed by fishing practices, which would suggest that many groundfish species have a truncated size (and age) structure from historical levels (Jennings and Blanchard 2004, Blanchard et al. 2005). Reference points have not been established for this indicator, but similar reference points have been suggested for the indicator mean size that would set reference points at the median size (age) of maturity.

The WCGTS collects otoliths for most managed species and age structure should be available for these species throughout the time series. Data for other species varies, but are typically limited to small spatial scales and to single estimates in time. The variability in age structure is not clearly understood across time and space in the CCLME for most species.

Fundamentally, the public can easily understand the importance of age structure to the success of fish populations—older individuals are generally larger and generally produce more and stronger offspring. Age structure is inherently used by policy makers because stock assessments use spawning stock biomass as the fundamental metric, which is related to the age of individuals when they mature.

Rebuilding timeline. For groundfish species in the PCGFMP, if a species population size is assessed to be less than 25% of its unfished spawning biomass, it is declared overfished and a rebuilding plan must be developed. A rebuilding plan establishes an allowable harvest rate that will enable the species to rebuild to its target spawning biomass (40% unfished spawning biomass) within an adequate period of time based on the minimum time of recovery, assuming no fishing (PFMC 2010a). The rebuilding timeline varies dramatically among species. For example, under current management harvest rates, cowcod (*Sebastes levis*) were predicted to rebuild by 2071, while widow rockfish (*Sebastes entomelas*) were predicted to rebuild by 2010 (PFMC 2010a). When management action is taken, such as reductions in harvest rate, most species stop declining, but the rate at which they rebuild varies (Miller et al. 2009). Rebuilding timelines are only developed for those species declared overfished, so there is a limited number with this information calculated. However, rebuilding timelines could be calculated from available data on other assessed species.

This indicator is relatively easy to understand by the public and policy makers. It is also easy to understand which species are having a difficult time rebounding from historical pressures.

Spatial structure of populations. The spatial structure is a measure of the geographic range and distribution of a species or stock. Most groundfish species in the PCGFMP are managed as a single stock, but there is mounting evidence that the genetic composition of recruits may be quite complicated spatially (Larson and Julian 1999, Berkeley et al. 2004b). Youngest recruits are found to have different genetic diversity and haplotypes from older year-classes or adults. This suggests that the geographic source of successful recruits may differ from year to year and that some populations may be reproductively isolated depending on oceanic conditions. Thus understanding how spatial structure may have changed over time may help our understanding of the connectivity of species across large spatial scales such as the CCLME. Distributional shifts are hypothesized to occur for either of two reasons—climatic or exploitation—but the difference is difficult to distinguish. Perry et al. (2005) showed large latitudinal shifts correlated with changes in temperature. Changes in depth distribution of groundfish assemblages have been found to be the result of changes in climate, while latitudinal shifts in distribution may be caused by either climate or exploitation (Fairweather et al. 2006, Coetzee et al. 2008, Dulvy et al. 2008).

As predicted, the geographic ranges of many overexploited species typically shrink, and stocks are concentrated into smaller regions following population declines (Atkinson et al. 1997, Garrison and Link 2000). Moreover, shrinking spatial distribution may limit the ability of a population to find suitable environmental conditions for offspring (Berkeley et al. 2004b). Some changes in species spatial distributions may even result in population extinctions (Thomas et al. 2004, Drinkwater 2005). Reference points for distributional shifts are not currently used and would be difficult to measure unless species were divided into distinct population segments and shifts away from one segment triggered management actions.

The WCGTS has collected data on the density and distribution of the CCLME groundfish assemblage for nearly 30 years. At this time, it is unknown whether shifts in the distribution of any species vary with changes in climate, exploitation, or changes in population condition.

In general, shifting or changing patterns of spatial distribution are easily understood by the public and policy makers. This type of information has been transmitted to the public in the past in the context of invasive species for terrestrial, freshwater, and marine systems. For example, the expanding geographic range of red lionfish (*Pterois volitans*) in the Caribbean may have started as a human introduction to the waters around Florida, but the subsequent movement to the rest of the Caribbean is clearly a spatial range expansion (Schofield 2009). The ability to detect spatial shifts in distribution or range is likely to occur at long time scales for noninvasive species, so spatial structure should be a lagging indicator of changes in the population condition.

Mean size of all species. The mean size (measured by length or weight) of all species caught in fishery-independent surveys, fishery-dependent surveys, or landings has been used to evaluate changes in an ecosystem (Link and Brodziak 2002, Link et al. 2002, Rochet and Trenkel 2003, Nicholson and Jennings 2004, Sala et al. 2004). A decrease in mean size is expected and has been observed in heavily fished systems (Haedrich and Barnes 1997, Levin et al. 2006, Methratta and Link 2006). However, the sensitivity of changes in mean size to environmental conditions is not well understood (Rochet and Trenkel 2003). One study suggests changes greater than 30% in mean length from one year to the next be set as a reference point (Link 2005), while another study suggests the reference point be set at the median length at maturity (Caddy and Mahon 1995).

In the WCGTS, subsamples of targeted species (up to 100 per trawl) are individually measured for length and weight. In order to monitor this indicator with fishery-independent data, all species would need to be sampled and measured in some fashion. However, this metric can be calculated using fisheries landings data (Link 2005), so historical data are available via Pacific Fisheries Information Network (PacFIN, http://pacfin.psmfc.org/).

This indicator is easily understood and is being used in other regional ecosystems (Link 2005). Similar to other indicators, mean size of all species is most likely to be a lagging indicator of the population condition because the size structure may be the result of environmental conditions acting on each individual since it was born.

Age at maturity. Population parameters such as age and size at maturity are adaptive traits and there is increasing support in the literature for rapid evolution of these life history characteristics (Haugen and Vøllestad 2001, Stockwell et al. 2003). As with the discussion of age structure as an indicator, significant changes in a population's age at maturity can signal extreme pressures that may have significant impact on a population's ability to sustain itself and ought to be cause for concern (Olsen et al. 2004). Declines in age-at-first-maturity have been commonly associated with compensatory responses to a reduction in population size (Trippel 1995, Berkeley et al. 2004b). There are multiple examples in which age at maturity has declined in heavily exploited groundfish populations such as Atlantic cod (*Gadus morhua*) (Beacham 1983a, Morgan et al. 1993), haddock (*Melanogrammus aeglefinus*) (Beacham 1983b), American plaice (*Hippoglossoides platessoides*) (Trippel 1995), and community-wide measurements (Greenstreet and Rogers 2006). In most studies, age at maturity declined during periods of exploitation, as evolutionary theory would predict, but striped bass (*Morone saxatilis*) in coastal Rhode Island showed a 15% increase in age at maturity over a 46-year period (Berlinsky et al. 1995). Olsen et al. (2004) provide a framework for Atlantic cod reference points that would provide managers with early warning signals about changes in this indicator.

Estimates of age at maturity exist for most managed groundfish species, but sampling generally occurred across short temporal scales (Gunderson et al. 1980, Echeverria 1987, see references within Love et al. 2002, Thompson and Hannah 2010). There are a few examples of multiple studies that measured age at maturity at various points in time at different locations within the CCLME, for example, canary rockfish (*Sebastes pinniger*) from California, Oregon, Washington, and British Columbia at various times between 1960 and 1982 (Phillips 1964, Westrheim 1975, Gunderson et al. 1980, Echeverria 1987). Age structures (otoliths, dorsal spines, and fin rays) are collected from targeted species during the WCGTS and gonads are collected as special projects from time to time. However, most groundfish are in need of new data on maturity and fecundity relationships, because methods have been inconsistent across studies and there are few examples of estimates over time (Stewart 2008).

Age at maturity is an easy indicator to understand for the public and policy makers, but this indicator has not been used because of the general lack of data over time for most species.

Ecosystem health

Community composition—*Zooplankton species biomass anomaly.* Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are the foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean ecosystem services. Zooplankton life cycles are short (on the order of weeks to a year) and populations have the potential to respond to and reflect event-scale and seasonal changes in environmental conditions (Hooff and Peterson 2006). Moreover, many zooplankton taxa are known to be indicator species whose presence or absence may represent the relative influence of different water types on ecosystem structure. Thus zooplankton may serve as sentinel taxa that reflect changes in marine ecosystems by providing early indications of a biological response to climate variability and are often used as an indicator to detect climate change or regime shifts (Hooff and Peterson 2006, Mackas et al. 2006, Peterson 2009). Finally, zooplankton are abundant and can be quantified by relatively simple and comparable sampling methods and, because few are fished, most population changes can be attributed to environmental causes (Mackas and Beaugrand 2010). As such, they may prove useful as a leading indicator of what may happen to regional commercial fish stocks several years later (Mackas et al. 2007, Peterson et al. unpubl. manuscr.).

All along the California Current, anomalies in zooplankton species composition shifts have been correlated with regional climate patterns (Mackas et al. 2006). For example, off the Oregon coast zooplankton indices have been developed based on the affinities of copepods for different water types: those with cold water and those with warm water affinities (Peterson et al. unpubl. manuscr.). The cold water group usually dominates the coastal zooplankton community during the summer (typically May through September) upwelling season, whereas the warm water group usually dominates during winter, although this pattern is altered during summers with El Niño events or when the Pacific Decadal Oscillation (PDO) is in a positive (warm) phase. Perhaps the most significant aspect of the copepod index is that two of the cold water species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich species. Therefore, an index of northern copepod biomass may also index the amount of wax esters and fatty acids being fixed in the food chain, compounds which appear to be essential for many pelagic fishes if they are to grow and survive through the winter successfully.

Several long-term zooplankton monitoring programs, representing seven subregions spanning the entire CCLME from Baja California to Vancouver Island, now provide zooplankton time series of various lengths from 1969 to the present. Although differences in processing and sampling zooplankton time series introduce a variety of biases that often prevent comparisons between data sets, many major questions can still be answered because an individual data set can be presented and analyzed as a time series of log-scale anomalies relative to the local long-term-average seasonal climatology. Anomalies are primarily used to separate interannual variability from the often large annual seasonal cycle of zooplankton stock size (Mackas and Beaugrand 2010). The specific species associated with these anomalies vary regionally, but can generally be classified as resident versus nonresident species. Regional anomalies can be combined into a single index using multivariate techniques (e.g., principal component analysis) in similar fashion to the calculation of regional climate indices, such as the Multivariate El Niño Southern Oscillation (ENSO) Index (Wolter and Timlin 1993). This index can then be tested for use as a leading indicator of regional climate signals, such as ENSO or PDO, using existing time series from the last 20 years, during which time the California Current saw at least two major climate regime shifts.

Zooplankton abundance and biomass. As noted above, zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change. As an important link at the base of the pelagic food web, they are considered a fundamental component in the CCLME (Brand et al. 2007, Horne et al. 2010, Sydeman and Thompson 2010). Because the biomass of planktivorous fish is inversely related to zooplankton biomass, which in turn is inversely related to phytoplankton biomass, zooplankton may prove useful as a leading indicator of what may happen to regional commercial fish stocks several years later (Sherman 1994, Mackas et al. 2007, Mackas and Beaugrand 2010, Peterson et al. unpubl. manuscr.). Zooplankton biomass declines have been correlated with warming of surface waters (Roemmich and McGowan 1995, Sydeman and Thompson 2010) and used to detect regime shifts (Hare and Mantua 2000). However, for time series observations of ecosystem state variables such as biomasses or chemical concentrations, standard deviations may increase, variance may shift to lower frequencies in the variance spectrum, and return rates in response to disturbance may decrease prior to a change (Carpenter et al. 2008).

The feeding effect of pink salmon (*Oncorhynchus gorbuscha*) has been shown to control summer macrozooplankton and phytoplankton biomass in the subarctic North Pacific (Shiomoto et al. 1997). Trophic cascade theory holds that reductions in harvest of zooplanktivorous fish would ultimately result in lower biomass of zooplankton, but it is unclear whether this has been demonstrated in the field for large marine systems (Pace et al. 1999). There are a number of (up to seven) long-term zooplankton biomass time series that have been maintained throughout various regions of the CCLME (Hooff and Peterson 2006, Mackas and Beaugrand 2010); one of the oldest of these data sets is the California Cooperative Oceanic Fisheries Investigative (CalCOFI) reports time series, which has been collected since 1956 (McClatchie et al. 2009). In freshwater systems, zooplankton biomass has been used as a leading indicator of trophic cascades.

Demersal fish biomass and trends (groundfish). The groundfish community of the CCLME consists of approximately 250 species or groups of fish (as detected in the WCGTS). This assemblage forms a large component of the ecosystem; thus changes in the status and trends of this group will impact the community composition of the ecosystem. Testing for changes in population size using individual species or groups of species has been used to assess community change using a variety of statistical approaches (e.g., Heessen and Daan 1996, Haedrich and Barnes 1997, McClanahan et al. 2010). In simulations of six northeast Pacific Ocean food web models, demersal fish biomass was significantly correlated with 9 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of total respiration/total biomass in the ecosystem and the best indicator of mean trophic level (Samhouri et al. 2009). However, changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted to be used for assemblages of fish such as groundfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) is available for all groundfish species susceptible to bottom trawling across the U.S. portion of the CCLME since 1977. There are also data available at smaller spatial scales and various temporal scales in untrawlable habitats from submersibles, remotely operated vehicles (ROVs), and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity are not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand the concept of groundfish and whether groundfish are trending up or trending down. In addition, policy makers have already used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of groundfish would likely be measured against long-term averages, so unless dramatic changes are observed, groundfish biomass will be a lagging indicator of changes in community composition. Moreover, groundfish have been a common assemblage to measure worldwide when trying to understand the structure of ecosystems or the consequences of pressures such as fishing or climate change (Link et al. 2002, Dulvy et al. 2006, Levin et al. 2006).

Flatfish biomass. There are approximately 24 species of flatfish detected in the WCGTS. Changes in flatfish biomass, particularly increases, are indicative of heavily fished ecosystems (Pauly 1979, Kaiser and Ramsay 1997, Hall 1999, Link 2005). In simulations of 6 northeast Pacific Ocean food web models, flatfish biomass was significantly correlated with 12 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of the ecosystem reorganization index (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as flatfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

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The public can easily understand whether flatfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of flatfish would likely be measured against long-term averages, so unless dramatic changes are observed, flatfish biomass will be a lagging indicator of changes in community composition. Monitoring flatfish biomass is consistently performed in other regions of the United States and in other nations because they have been shown to respond to exploitation (Pauly 1979, Kaiser and Ramsay 1997, Hall 1999, Link 2005).

Roundfish biomass. There are approximately 103 species of roundfish detected in the WCGTS. We define roundfish similarly to Samhouri et al. (2009), as species in the following families: Anoplopomatidae, Cottidae, Gadidae, Hexagrammidae, Macrouridae, Merlucciidae, and Scorpaenidae. In simulations of 6 northeast Pacific Ocean food web models, roundfish biomass was significantly correlated with 9 of 22 different ecosystem attributes; however, roundfish biomass was not the best indicator (out of 27 candidate indicators) of any one ecosystem attribute (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as roundfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available for all roundfish species susceptible to bottom trawling across the U.S. portion of the CCLME since 1977. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersibles, ROVs, and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity is not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand whether roundfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of roundfish would likely be measured against long-term averages, so unless dramatic changes are observed, roundfish biomass will be a lagging indicator of changes in community composition. Monitoring roundfish biomass is consistently performed in other regions of the United States and in other nations.

Rockfish biomass. There are approximately 61 species of rockfish detected in the WCGTS. Rockfish are of conservation concern because they are generally targeted or captured as bycatch in several West Coast fisheries. Rockfish are long-lived species, often exceeding 50 years (Love et al. 2002). Rockfish also grow slowly and mature relatively late compared to other fishes. This life history strategy helps rockfish populations persist through poor environmental conditions. However, this strategy also inhibits their ability to recover from high levels of exploitation. Rockfish occupy a broad range of habitat and trophic roles. In simulations of 6 northeast Pacific Ocean food web models, rockfish biomass was significantly correlated with 9 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of the piscivorous fish reorganization index (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as rockfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available since 1977 for all rockfish species susceptible to bottom trawling across the U.S. portion of the CCLME. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersibles, ROVs, and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity are not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand whether rockfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of rockfish would likely be measured against long-term averages, so unless dramatic changes are observed, rockfish biomass will be a lagging indicator of changes in community composition. Monitoring assemblages such as rockfish is consistently performed in other regions of the United States and in other nations.

Adult sablefish biomass (correlation to Shannon Diversity Index). Theoretical modeling results have been used to show that some ecosystem structural (e.g., diversity) attributes can be related to thresholds in the level of human-induced pressure. In particular, a marine ecosystem model for British Columbia was used to show that sablefish density is positively correlated with Shannon Diversity, suggesting that changing levels of fishing on a particular species may produce substantial improvements toward protecting ecosystem goals based on this structural attribute (Samhouri et al. 2010). The model also describes how to incorporate uncertainty into the estimation of utility thresholds and their value in the context of understanding EBM trade-offs. These modeling results may be equally applicable to the CCLME because of many similarities between these ecosystems. The value of this indicator is predicated not only on the correlation between sablefish biomass and ecosystem diversity, but also on how well each of these independent indicators meet individual evaluation considerations.

With regard to biodiversity, Shannon Diversity is a measure that incorporates both richness (the number of different species within a system) and evenness (the number of individuals of each species within a system). The correlation between diversity and ecosystem function (productivity and stability) has been reviewed recently for terrestrial and marine systems, suggesting that the relationship is complex but communities are more stable at higher richness (Hooper et al. 2005, Stachowicz et al. 2007). In general, populations can be more variable but community level processes are more stable at higher diversity (i.e., the biomass of species A and species B may fluctuate, but A + B tends to be stable). Linking diversity indices to targets or reference points is difficult, and the significance of certain types of change is not known for biodiversity indices (Link 2005, Dulvy et al. 2006). Furthermore, the general public tends to have a basic understanding and positive impression toward biodiversity as it relates to ecosystem health (Thompson and Starzomski 2007). Species richness has been shown to decrease with fishing, although these results appear largely related to trawling and dredging on benthic invertebrates (Gaspar et al. 2009, Reiss et al. 2009).

Shannon Diversity indices can be used with a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), invertebrates from benthic grabs conducted by the EPA Environmental Monitoring and Assessment Program's National Coastal Assessment (http://www.epa.gov/emap/index.html), and a variety of seabird and marine mammal surveys (Barlow and Forney 2007, Carretta et al. 2007, McClatchie et al. 2009, Ainley and Hyrenbach 2010). For their biomass, sablefish have a wide distribution, and populations are managed and evaluated on the west coast of North America using stock assessments that are calculated from abundance estimates (Keller et al. 2008, PFMC 2008b). Increased fishing pressure leads to lower sablefish biomass and populations have been shown to vary with decadal-scale climate regimes (King et al. 2000, 2001). Bioenergetics models have also been used to examine the effects of temperature change on sablefish, but not specifically with regard to changes in biomass or population size (Harvey 2009).

Coho salmon smolt-to-adult survival rate. The salmon smolt-to-adult survival rate is considered a good indicator of the state of the CCLME because salmon populations are highly influenced by ocean conditions, and coho salmon marine survival in particular is significantly and independently related to the dominant modes acting over the coastal region in the periods when the coho first enter the ocean (Koslow et al. 2002, Logerwell et al. 2003, Scheuerell and Williams 2005, Peterson et al. unpubl. manuscr.). Furthermore, salmon are of high commercial, recreational, and cultural importance along much of the Pacific coast, and therefore have high relevance in the delivery of ocean ecosystem services to the region (NRC 1996). Strong coupling has been demonstrated between smolt-to-adult survival and ocean upwelling in the spring and fall, suggesting management policies directed at conserving salmon need to explicitly address the important role of the ocean in driving future salmon survival (Scheuerell and Williams 2005). Furthermore, the salmon smolt-to-adult survival rate may affect management as it relates to using ocean conditions to determine best release date of hatchery fish.

The Oregon Production Index (OPI), defined as the percent of smolt-to-adult returns for coho salmon in Oregon, is currently one of several time series considered useful ecosystem indicators within the California Current region (Peterson et al. unpubl. manuscr., Sydeman and Thompson 2010). This data set is temporally extensive and comprehensive for the central CCLME (PFMC 2010b). However, it is considered a lagging or retrospective indicator of ocean conditions due to the protracted life cycle of salmon (Scheuerell and Williams 2005, Peterson et al. unpubl. manuscr.).

Biodiversity index. Hurlbert's delta is a measure of taxonomic evenness that, when applied to abundance estimates from a particular ecological community, estimates the probability of two individuals in a sample being different species (Hurlbert 1971). It has a clear, concise ecological interpretation and has been applied as an indicator for detecting the impact of fishing on a fish community (Trenkel and Rochet 2003). Linking diversity indices to targets or reference points is difficult, and the significance of certain types of change is not known for biodiversity indices (Link 2005, Dulvy et al. 2006). Hurlbert's delta measure has been applied in measuring detectable spatial variation with depth and latitude at large scales and, although temporal patterns may be unknown, could be calculated from historical data (Tolimieri 2007). It can also be used to detect changes in community composition after change has occurred, although natural and baseline levels of taxonomic evenness may vary so much that absolute values may not be comparable in terms of thresholds.

Other studies have shown biodiversity trends in the Bering Sea correlate with regime shifts (Hoff 2006). The same approach could be applied to a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), invertebrates from benthic grabs conducted by the EPA EMAP National Coastal Assessment (http://www.epa.gov/emap/index.html), and a variety of seabird and marine mammal surveys (Barlow and Forney 2007, Carretta et al. 2007, McClatchie et al. 2009, Ainley and Hyrenbach 2010).

Proportion of noncommercial species. The proportion of noncommercial species in groundfish survey data has been shown to be strongly related to 12 attributes of ecosystem health, based on modeling results from numerous systems (Samhouri et al. 2009). It has been used as one of the more sensitive indicators for detecting the impacts of fishing on fish communities, with a coefficient of variation around 20% for either biomass or abundance (Trenkel and Rochet 2003). Modeling results show the proportion of noncommercial species responds to variation in fishing pressure and correlates to ecosystem attributes (Samhouri et al. 2009). If this indicator is monitored, gradual change should be detected prior to major community reorganization (i.e., leading indicator). Data for this indicator include a limited number of time series with good spatial coverage: Marine Recreational Fisheries Statistics Survey (MRFSS 1980–2003) data for nontrawl species (http://www.recfin.org/) and data from the observer program (bycatch species) (Bellman et al. 2009).

Juvenile rockfish abundance indices. Indices of larval or juvenile fish abundance can be good indicators of adult biomass and often play a useful role in stock recruitment models that forecast year-class strength (Bailey and Spring 1992, Ralston and Howard 1995). Long-term trends in larval abundance can reflect trends in adult biomass, whereas short-term fluctuations are likely related to episodes of high or low reproductive output or geographic shifts due to animal movement (Hsieh et al. 2005). Larval fish surveys from CalCOFI reports have provided some of the first empirical evidence to show that fishing increases variability in the abundance of exploited populations, even after accounting for life history effects, ecological traits, phylogeny, and a changing environment (Hsieh et al. 2006). Rockfish and hake both have significant commercial and recreational importance and play an important role in the delivery of a variety of ocean ecosystem services to the region.

Larval fish surveys have been conducted over the central California coastal region since 1983, with a 2004 expansion of the survey area to the U.S.-Mexico border (Brodeur et al. 2003, Sakuma et al. 2007, Helser and Martell 2007), and therefore have limited spatial coverage within the CCLME. A juvenile rockfish index is currently used as 1 of 20 time series considered useful ecosystem indicators within the CCLME (Sydeman and Thompson 2010). Larval fish abundance indices have been used as ecosystem indicators in other regions, such as the North Sea (Frederiksen et al. 2006).

Juvenile hake abundance. See *Juvenile rockfish abundance indices* subsection above.

Crustacean survey trends. Crustaceans are a prominent component of the CCLME and contribute to the delivery of several important ecosystem services in the region through commercially and recreationally important fisheries (Fogarty and Botsford 2006). They also comprise several important predatory and scavenger groups in existing CCLME models (Brand et al. 2007). They are highly responsive to top-down effects in the food web, and predatory finfish abundance may be a negative indicator for invertebrate fishery productivity (Caddy 2004). For instance, shrimp biomass has been strongly negatively related to cod biomass in the North Atlantic Ocean, showing that changes in predator populations can have strong effects on prey populations in oceanic food webs (Worm and Myers 2003). Fishing effects may exacerbate these patterns: the Gulf of Maine shifted from a high trophic level, groundfish-dominated, system to a low trophic level, crustacean-dominated system during the 1980s to 1990s (Zhang and Chen 2007).

As a group, crustaceans are often found low in the food web, are highly fecund, and may be sensitive to bottom-up effects; therefore, indicators measuring plankton productivity, turbidity, oxygen levels, and eutrophication should be useful in predicting the typically large variations in recruitment success that drive these fisheries (Caddy 2004). Climate change manifested in water column temperature also has an effect on lower trophic levels of boreal marine ecosystems, and changes in crustacean recruitment patterns may be one of the first indicators of community regime shift (Zheng and Kruse 2000). For instance, declines in several species of pandalid shrimp and other community effects in the Gulf of Alaska have been attributed to climate induced changes in water column temperature (Anderson 2000). Pandalid shrimp surveys are also used as indicators of Pacific Ocean conditions off British Columbia (DFO 2009). The abundance of decapod larvae in the plankton also appears to be positively correlated to changes in North Sea sea surface temperature (SST) (Kirby et al. 2009).

For the most part, data availability for this group is relatively good. Zooplankton time series are spatially and temporally extensive (Mackas et al. 2007, McClatchie et al. 2009), and crustacean larval surveys represent a long established means of estimating the spawning stocks of decapods (Kirby et al. 2009). Harvest data records are fairly extensive through PacFIN (though biased by typical catch issues) and some aspects of the ongoing West Coast groundfish surveys may be useful in deciphering abundance/biomass patterns (Keller et al. 2008).

Kelp forest coverage. Kelp forests are ecologically and economically important, as they are the foundational structure for diverse communities in most coastal waters of the CCLME (Dayton 1985, Graham 2004). The persistence of many biologically and commercially important species of algae, invertebrates, fish, and marine mammals are directly coupled to the production of energy from kelp (Foster and Schiel 1985, Steneck et al. 2002). Kelp forests may also serve functional roles in cycling carbon between coastal marine, littoral (Polis and Hurd 1996, Dugan et al. 2003), and continental shelf (Harrold et al. 1998, Vetter and Dayton 1999) ecosystems. Most kelp forests exist in waters less than 60 m deep, so at the scale of the CCLME community composition may not be tied to the abundance of kelp, but because of its importance as essential fish habitat for many species of concern, including young-of-year (Carr 1991), understanding the temporal variation and spatial heterogeneity (Jones 1992, Bustamante and Branch 1996) of kelp forest coverage in the CCLME may be a useful indicator of ecosystem structure. Following the framework of Link (2005), reference points related to percent change in aerial coverage of kelp could be established.

The density and distribution of kelp forests have been measured historically in numerous ways. Many historical data sets include scuba diving surveys (e.g., Partnership for Interdisciplinary Studies of Coastal Oceans [PISCO] at http://www.piscoweb.org/, U.S. National Park Service at http://www.nps.gov/chis/contacts.htm), but these are generally over small spatial and short temporal scales. Recent advances in satellite and infrared photography have allowed researchers to measure areal canopy cover and biomass of kelp along much of the U.S. West Coast (Deysher 1993, Cavanaugh et al. 2010).

Kelp forest coverage is easily understood by the public and has been used by policy makers to develop guidelines related to provisions of the marine statistical area on the identification of essential fish habitat (16 USC §1855b). Changes in kelp forest coverage affect recruitment of invertebrates and other species (e.g., Carr 1991), such that kelp forest coverage could anticipate recruitment of older life stages into the bottom trawl surveys or into the fishery; thus kelp forest coverage could be a leading indicator for the community composition of the CCLME.

Number of threatened species. This is a composite indicator based on a weighted average of species threat, as determined by the International Union for the Conservation of Nature (IUCN 2008), which may be different from those considered threatened under the U.S. Endangered Species or Marine Mammal Protection acts. This is essentially a richness survey, and although the relationship between richness and function is complex, communities appear to be more stable at higher richness (Stachowicz et al. 2007).

Richness can influence stability and productivity in two ways: sampling/selection effect or compensatory effect (Stachowicz et al. 2007). Under the sampling effect, higher richness leads to a greater chance of highly productive species being present. This type of relationship is not considered a real richness effect by some, but more of a compositional or keystone species effect. Under the compensatory effect, higher production or stability occurs in two ways: via resource complementarity, where more species occupy more niches and better utilize all resources (e.g., different type of nitrogen), and facilitation, where some species combinations do better. However, it is not always clear how to relate species richness or other diversity measures to reference points or targets (Hooper et al. 2005, Link 2005), although some authors have provided a rationale to manage for biodiversity as an approach to EBM (Palumbi et al. 2009).

Species richness has been shown to decrease with fishing, although these results appear largely related to trawling and dredging on benthic invertebrates (Gaspar et al. 2009, Reiss et al. 2009). The weighting criteria for this indicator are somewhat arbitrary and linking the index to targets or reference points is difficult; however, data are readily available and numerical. The same approach used by the IUCN could be applied to a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), and a variety of seabird and marine mammal surveys (Gislason et al. 2000, Dulvy et al. 2006, McClatchie et al. 2009).

Taxonomic distinctness. Measures of community diversity are directly indicative of ecosystem structure and can be used to test for effects of environmental pressures on various communities (Gaspar et al. 2009, Reiss et al. 2009). In general, communities are considered more stable at higher measures of diversity (Stachowicz et al. 2007). Taxonomic distinctness (TD) is a measure of diversity based on the relatedness of species in a sample and incorporates the evolutionary history of ecosystem constituents. For example, a sample with two rockfish of different species would be considered less taxonomically distinct or diverse than a sample with one rockfish and one flatfish.

Average taxonomic distinctness (AvTD) is the mean of all species-to-species distances through a taxonomic classification tree for all species pairs within a sample and represents the taxonomic breadth of the sample. Gristina et al. (2006) found lower TD in trawled versus untrawled habitats and TD was higher in marine reserves versus fished areas (Stobart et al. 2009). Variation in taxonomic distinctness (VarTD) is the variation in branch lengths among all species pairs (not the variance of AvTD among samples) and is a measure of the irregularities and divergences in the distribution of branch lengths within a sample. Latitudinal and depth related variation in AvTD and VarTD on the West Coast are described by Tolimieri and Anderson (2010). Defining reference points for measurements of diversity is difficult (Link 2005, Dulvy et al. 2006).

Both indices are appealing because they are based on presence/absence data and, unlike many biodiversity measures, neither is affected by the number of species or the sampling effort. In the present case, these properties allow one to compare the bottom trawl survey data from the AFSC and NWFSC as evidenced by the close agreement in AvTD and VarTD values for 2004 (see EBM Component, Ecosystem Health subsection). Data are available to investigate TD for intertidal invertebrates from 2002 to 2010 (PISCO at http://www.piscoweb.org/) and zooplankton across various regions of the CCLME for varying periods of time (e.g., NWFSC, Newport Line, CalCOFI survey). Other data sets are also available at smaller spatial and temporal scales (e.g., National Park Service kelp forest monitoring program in the Channel Islands). Many of these data sets will need to be combined to investigate trends in TD over time across the entire scale of the CCLME. Statistical tools have been developed that take into account the uncertainty associated with multiple data sets so they can be combined (Drake et al. 2010).

Trends in TD and the fundamental idea of diversity are easily understood by the public and policy makers. Increases or decreases in TD would certainly be a lagging indicator of changes in ecosystem structure.

Scavenger biomass. Scavengers play significant roles in the ecosystem by recycling dead and decomposing organic matter back into the food web. However, human interference in the marine ecosystem has likely increased the abundance and number of species that forage on carrion (Britton and Morton 1994). For example, many fishing operations discard dead bycatch to the ocean floor or damage organisms on the seabed during bottom fishing operations (Ramsay et al. 1998). Scavenger population increases may be related to these types of fishing activities (Britton and Morton 1994, Ramsay et al. 1998, Demestre et al. 2000). Scavengers are typically defined by the proportion of carrion or detritus in a species' diet.

When evaluating this indicator, we use the definition of scavenger used in the Atlantis ecosystem models for the California Current (Brand et al. 2007, Horne et al. 2010). In these models, scavengers include all large crabs, large demersal sharks, grenadiers, deposit feeders (i.e., isopods and amphipods), and carnivorous infauna such as polychaetes. Detectable changes in the attribute community composition may be a result of changes in various foraging guilds, but a change (or no change) in a single guild may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted and used for foraging guilds such as scavengers. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available since 1977 for all scavenger species susceptible to bottom trawling across the U.S. portion of the CCLME. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersible, ROV, and the NWFSC hook-and-line surveys. Fishery-dependent data for crab species are available in the PacFIN database (http://pacfin.psmfc.org/). Some species of the scavenger guild, such as isopods, amphipods, and polychaetes, will need new surveys to quantify these components. Benthic grab samples are commonly used to quantify benthic infauna, but it may be difficult to perform this type of survey at the scale of the CCLME at necessary temporal scales. Moreover, quantifying a value for many foraging guilds will require quantitative analyses to combine data sets which collect data using very different methods. For example, bottom trawl surveys, longline surveys, and benthic grab samples will need to be combined at various spatial and temporal sampling scales to quantify the biomass of grenadiers, crabs, large demersal sharks, and deposit feeders.

The public can easily understand whether a foraging guild, such as scavengers, is trending up or down, but this particular indicator may be less attractive to the public than more charismatic groups (i.e., marine mammals or sharks). Detecting changes in the biomass of scavengers would likely be measured against long-term averages, so unless dramatic changes are observed, scavenger biomass will be a lagging indicator of changes in community composition. Monitoring foraging guilds such as scavengers has been performed in other regions of the United States (Link and Almeida 2002) and in other nations (Demestre et al. 2000, Greenstreet and Rogers 2000).

Energetics and material flows—*Number of cycles.* Carbon cycling, or the flow of energy within an ecosystem, has increasingly been estimated in the CCLME and elsewhere using mass-balance models (e.g., Atlantis and EcoSim) (Christensen and Walters 2004, Fulton et al. 2005, Brand et al. 2007, Horne et al. 2010). One ecosystem indicator that has been measured with the aid of these models is the number of cycles inherent in a particular system (Baird et al. 1991). From a theoretical standpoint, carbon cycling should decrease predictably as ecosystem stress increases, stability decreases, and the system becomes more open to carbon inputs and removals (i.e., as internal cycling is reduced) (Odum 1985, Link 2005, Gaichas et al. 2009, Samhouri et al. 2010). Carbon cycling is therefore highly relevant to various human activities, such as fishing, where biomass is removed from a system, or climate change, where carbon sequestration decreases. The number of carbon cycles in a system should respond predictably to management actions such as fishing closures where cycling should increase as top predators rebuild.

The modeling approach itself, though subject to a number of large assumptions, is operationally simple and robust to a variety of data issues, allowing historical simulations over a broad spatial range. It is also increasingly used by policy makers as a cost effective tool to predict and anticipate management actions and valuable as a comparative tool between other ecosystems and historic states (Baird et al. 1991, Fulton et al. 2005, Gaichas et al. 2009, Samhouri et al. 2010). Model calibration itself involves substantial preparation and trial and error, and there are numerous uncertainties and assumptions associated with estimating biomass of various trophic groups using incomplete survey or census data (Hill and Wheeler 2002).

Inorganic nutrient levels (phosphate, nitrate, silicate). The availability of inorganic nutrients in the euphotic zone acts as a control on biological production in the California Current ecosystem (McGowan et al. 2003). In general, the open waters of the CCLME are nutrient limited, with nutrient pulses characterized by upwelling events and to a lesser degree, river plumes (Hill and Wheeler 2002). Therefore, anomalies in nutrient levels or periodicity represent a leading indicator of changing upwelling patterns, hydrographic and flow alterations, climate change, or regime shifts that effect subsequent patterns of biological production. Although eutrophication is not common in the open waters of the CCLME, increased nutrient turnover and decreased cycling frequently appear in stressed ecosystems, and together result in accumulation of nutrients which, like unused production, may be lost from the system (Odum 1985).

The eutrophication of estuaries and coastal seas is one of the best-documented and best-understood consequences of human-altered nutrient cycling; consequently, nutrient levels are often the focus in water quality monitoring programs. However, altered nutrient levels have not performed strongly as an indicator of fishing in ecosystem simulation models (Fulton et al. 2005). Nevertheless, alterations to the global nitrogen cycle have caused changes in the composition and functioning of estuarine and nearshore ecosystems and contributed to long-term declines in coastal marine fisheries (Vitousek et al. 1997). At the same time, some nearshore species (e.g., bull kelp [*Nereocystis luetkeana*]) in the California Current may be especially sensitive to episodic events that limit intrusion of deep, cooler, nutrient-rich waters from offshore (McGowan et al. 2003).

For offshore regions, nutrient levels in the upper layers of the water column have generally been poorly characterized in space and time (Hill and Wheeler 2002). Some notable exceptions to this pattern include intensive sampling at individual regions: the southern California Current via the CalCOFI report program (McClatchie et al. 2009) and portions of the northern California Current via U.S. Global Ocean Ecosystems Dynamics (GLOBEC) cruises. Most nutrient levels (nitrate, phosphate, silicate) are characterized in the CalCOFI region from 1984 to present based on concentration anomalies in the mixed layer depth (McClatchie et al. 2009). In notable contrast to offshore regions, nutrient concentrations in nearshore regions of the California Current have been more or less continuously measured in many rivers, estuaries, beaches, and other drinking water supplies for decades; some examples include Washington State's Olympic Region Harmful Algal Bloom (ORHAB) program and the Monterey Bay National Marine Sanctuary Program.

Chlorophyll a. Chl *a* can be used as an indicator of phytoplankton biomass, which itself is a good indicator of the amount of energy fueling the ecosystem (Falkowski and Kiefer 1985, Cole and Cloern 1987, Polovina et al. 2001, Edwards and Richardson 2004, Fulton et al. 2005). The amount of primary productivity, measured as total chlorophyll per unit area (mg m^{-3}), has been recognized as an important aspect of the marine food web, and chl *a* values are used to estimate phytoplankton biomass for mass-balance models of the CCLME (Falkowski and Kiefer 1985, Brand et al. 2007, Horne et al. 2010). Chl *a* has been shown to respond predictably to reductions or increases in nutrient inputs (eutrophication). It should be possible to identify time-specific and location-specific limit reference points for upwelling or transition fronts, although the relationship between reflectance and phytoplankton biomass must be derived before this can be accomplished.

Chl *a* has been used to provide basic data for CCLME ecosystem model building and calibration based on values from GLOBEC sampling cruises between 1997 and 2004 and CalCOFI cruises from 2000 to 2004 (Brand et al. 2007). Satellite remotely sensed chl *a* concentration (mg m^{-3}) data can be obtained at minimal cost from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS at http://oceancolor.gsfc.nasa.gov/SeaWiFS/) to derive broad-scale coverage of values over the CCLME (Polovina and Howell 2005) or at smaller regional scales (Sydeman and Thompson 2010). Phytoplankton color, a visual index of chlorophyll derived from continuous plankton recorder surveys (http://www.sahfos.ac.uk/about-us/cpr-survey/the-cpr-survey.aspx), can also be used to show intensity and seasonal extent of chl *a* (Edwards and Richardson 2004). Some species or subsets of species of phytoplankton that affect chl *a* concentration can serve as an indicator of change in phytoplankton biomass, but physical measurements of upwelling intensity may provide a better leading indicator.

Evaluating Potential Indicators for the California Current: Salmon and Green Sturgeon

Initial Selection of Indicators

The selection of indicators for salmon and green sturgeon in the CCLME did not replicate the comprehensive literature-based evaluation used for groundfish and ecosystem health. Rather, the initial indicator list was compiled and refined based on the expertise of biologists currently studying these species. Future versions of the IEA will seek to expand the indicator vetting process for these species to enhance its transparency and comprehensiveness.

Salmon

Population size—For population size, we evaluated three primary indicators: 1) spawning escapement, 2) population growth rate, and 3) hatchery contribution. These indicators are supported by all of our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each of these three indicators was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

Spawning escapement. Estimates of spawning escapement are extremely important to salmon management. Ultimately, management is designed to meet escapement goals such that the population remains viable (for ESA-listed populations) or near the biomass that produces maximum recruitment (for stocks covered by a fisheries management plan). If the number of spawners falls too low, whether due to overfishing or natural mortality, the fishery could be closed as it was in 2008 and 2009.

Population growth rate. Calculated as the proportional change in abundance between successive years, population growth rate is an indication of the population's resilience. In addition, growth rate can act as a warning of critical abundance trends that can be used for determining future directions in management. Also, the viability of a population is dependent in part on maintaining life history diversity in the population.

Hatchery contribution. Hatchery production is a relatively homogeneous life history type relative to naturally produced populations. If natural production is reduced, the population can be at risk during periods of increased environmental variability (Lindley et al. 2007).

Population condition—For the attribute population condition, we identified and evaluated three potential indicators: 1) age structure, 2) spatial stock structure of stocks, and 3) size at age. These indicators are supported as indicators of population condition by our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each of the three indicators was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

Age structure. A diverse age structure is important to improve the population viability. Larger, older Chinook salmon produce more and larger eggs (Healey and Heard 1983). Therefore, they produce a brood that may contribute proportionally more to the later spawning population than broods from younger, smaller fish. However, the diversity of ages including younger fish is important to accommodate variability in the environment. If mortality on any given cohort is great, there is benefit to having younger spawners. This bet hedging is a critical aspect of Chinook salmon that allow it to naturally mitigate year-to-year environmental variability (Heath et al. 1999).

Spatial stock structure. Maintaining a metapopulation is critical to improving population viability. The limited connectivity between subpopulations allows each to act somewhat asynchronously. Therefore, the collapse of one subpopulation may not affect, in any dramatic manner, the viability of another subpopulation. Further, the subpopulation that experienced the collapse can be rebuilt by the limited connections it has with the remaining subpopulations. In the event that bridges between subpopulations are fragmented, the chance of extirpation is great, such has happened with the construction of dams across the California Central Valley (Schick and Lindley 2007).

Size at age. Size at age is an easily measured indicator of the growing conditions of populations that may be related to population growth rate. Also, management is designed to use average size at age to set size limits in the fishery. Therefore, variations in size at age can lead to variations in the age structure of the catch year-to-year, which could translate to changes in the age structure of the population at large.

Green Sturgeon

Population size—Compared to groundfish and salmon, green sturgeon have been little studied until quite recently and indicators are in the early stages of development. In light of the kinds of data that have been and are now beginning to be collected, just a few indicators relevant to green sturgeon will be possible to estimate. These include: 1) abundance of mature individuals in spawning rivers, 2) the catch of juvenile sturgeon in fish traps at large water diversions, and 3) the distribution in time and space of adult and subadult green sturgeon in rivers, estuaries, and the coastal ocean.

Abundance of mature individuals. Abundance is being estimated systematically for the first time in 2010, using sonar and underwater video to count green sturgeon in their summer holding pools on the Sacramento, Klamath, and Rogue rivers. Over time, these surveys can be repeated to generate estimates of population growth rate.

Catch of juveniles. Catch of juvenile green sturgeon in fish traps at large water diversions is available for the past several decades, and will likely be available for some time in the future until a planned major reorganization of water infrastructure in California’s Central Valley radically alters the hydrology and operation of the pumping plants (Scheiff et al. 2001, LHC 2010). Catches at these pumping plants may be an index of recruitment to the population, although the factors affecting the sampling performance of these pumps are unknown.

Population condition—Two indicators of population condition will be evaluated: 1) age structure and 2) spatial structure of subpopulations.

Age structure. Green sturgeon population age structure will be evaluated as an indicator of population condition in 2011.

Spatial structure of subpopulations. Tagging studies of green sturgeon conducted by the SWFSC and NWFSC have collected a large amount of data on habitat associations and movement of green sturgeon within and among the coastal Pacific Ocean, spawning rivers, and estuaries of nonnatal rivers. These data are being used to create dynamic models of green sturgeon distribution. A spawning river model for the Sacramento River has been completed (Mora et al. 2009) and a marine distribution model is in development.

Top Indicators

Salmon

Population size—*Spawning escapement.* Spawning escapement is the metric used to determine the allowable catch of salmon at sea and in-river. Therefore, these estimates are subject to extensive review (PFMC 2010c). In addition, the data have a record of more than 30 years. Variability in spawning escapement values represents changes in fisheries as well and changes in production and natural mortality. For Central Valley and Klamath River Chinook salmon populations, estimates of fishery catches can be added to escapement estimates to achieve estimates of total abundance (e.g., Sacramento Index) which is ultimately a measure of production. Specifically, total abundance is estimated a year in advance of the fish returning to spawn. The difference between total abundance and minimum spawning escapement thresholds is considered available to catch. In 2008 and 2009, these estimates indicated there were not enough fish available to open the fishery; therefore, fishing was closed for California coastal and inland waters.

Population growth rate. Not directly used in fishery management, population growth rate can be used to inform managers regarding population trends. The summed value of escapement and total catch offers reliable and peer-reviewed estimates of abundance between years (PFMC 2010c). Simply, growth rate can be estimated as the change in these values over time. Growth rate estimates have become critical recently when questions of resilience and population recovery are paramount. Furthermore, population growth rate estimates are an important component of status reviews conducted under the ESA (Good et al. 2005) and are a major component of viability criteria for Central Valley winter and spring Chinook (Lindley et al. 2007).

Hatchery contribution. Not directly used in fishery management, hatchery contribution is a component of viability criteria for Central Valley winter and spring Chinook salmon (Lindley et al. 2007). Recent declines in the abundance of fall-run Chinook stocks have required a reevaluation of how a more diverse wild and hatchery population structure could have improved resiliency to environmental perturbations (Lindley et al. 2009b). The estimates of hatchery contribution used here are considered to be underestimates, as they do not account for straying of hatchery fish from the hatcheries. Hatchery release locations are often great distances from the hatcheries themselves (e.g., directly into the estuary); therefore, natal homing of the later spawning salmon is compromised. Such concerns are confirmed by Barnett-Johnson (2007) wherein otolith chemistry and microstructure were used to determine that the hatchery contribution to the California coastal fishery may be as great as approximately 90%. Unfortunately, the time series of otolith data sets is too short to yield useful indicators in an IEA assessment. California has embarked on a constant fractional marking program that will allow robust estimation of hatchery contribution rates to fisheries and natural escapement areas, with such data to become available in the near future.

Population condition—*Age structure.* Age structure is considered in the management of Klamath River Chinook salmon populations (Farr and Kern 2005). Appropriate tagging of hatchery fish enables cohort reconstructions. The age structure represents the amount of mixing between cohorts and a wide age distribution is preferred so the population can remain viable if recruitment of any given cohort is compromised (e.g., 2004 and 2005 broodyears). Therefore, a diverse age structure is appreciated by managers as an indication of the population's resiliency (Farr and Kern 2005). Changes in age structure indicate variability across cohorts that could relate to variability in production, fisheries, and natural mortality.

Unfortunately, age structure cannot be determined for Central Valley stocks, as standardized proportional tagging and in-river surveys are only now being implemented.

The age structure of coho salmon is less of a concern, as the vast majority of cohorts practice the same life history such that the age structure of the population remains relatively stable. However, trends in early maturation of males (jack rates) are available. Some degree of early maturation is important to maintain mixing between cohorts. Females typically represent a very small proportion of the early maturing fish.

Spatial structure. Spatial structure of subpopulations is considered largely in management of the freshwater systems used by salmon. For instance, rebuilding the spatial structure of Central Valley and Klamath River salmon is a critical aspect of habitat rehabilitation and dam removal considerations. Improving salmon metapopulation dynamics and genetic diversity will increase the resiliency of the fish to environmental perturbations in freshwater and ocean arenas (Schick and Lindley 2007, Lindley et al. 2009b).

Size at age. Management is designed to use average size at age to set size limits in the fishery. Therefore, variations in size at age can lead to variations in the age structure of the catch year-to-year, which could translate to changes in the age structure of the population at large.

Size at age indicates variability in the growth of salmon from a cohort and can indicate conditions experienced at sea (Wells et al. 2006, Wells et al. 2007, Wells et al. 2008). There are large, coded-wire tag data sets that can be used to estimate the size at age of fish captured at sea and on the spawning grounds. These data have been successfully used in the past by Wells et al. (2006) to demonstrate how large-scale factors (e.g., ENSO and PDO) affect size at age. These tagging data sets go back more than 30 years.

Green sturgeon

Top indicators of green sturgeon will be evaluated and selected in 2011.

Suite of Indicators for the California Current

Based on the selection, evaluation, and ranking described in the previous subsections, we provide a framework for identifying a suite of indicators to evaluate the current status of the CCLME relative to historical conditions. This IEA report evaluates indicators for a subset of the seven EBM components. Due to the ultimate number of indicators that will be identified, evaluated, and selected for each of seven EBM components, we decided to limit each key attribute of each component to between two and four indicators.

Complementarity of Indicators

For the EBM components groundfish and ecosystem health, we used complementarity to narrow the list of top-ranked indicators for each key attribute. We compared highly ranked indicators across key attributes and EBM components and selected indicators that complemented each other in either the taxa or processes they represented. For example, many fish functional groups ranked highly as indicators of ecosystem health, but because many of these groups were also highly ranked indicators of groundfish, we did not select them for ecosystem health. Below we describe the full suite of indicators chosen for each key attribute of each EBM component and discuss the final selection process.

Groundfish

Population size—From the eight indicators in the top quartile for population size, we propose to use these three as indicators for population size of groundfish in the CCLME:

- Abundance of groundfish (numbers) in large-scale bottom trawl surveys
- Population growth rate
- Number of species below management thresholds

We chose to use numerical abundance of groundfish in bottom trawl surveys because whole-population stock assessments (another indicator in the top quartile) already exist and supply estimates of population size in spawning stock biomass. Abundance in numbers provides another useful indicator of trends in the population. Numbers of individuals in a population are also a metric of conservation importance and easy to understand in the policy arena. We did not choose hake acoustic survey biomass because it is limited to monitoring hake, while hake numbers can be monitored for trends in the bottom trawl survey. We chose number of species below management thresholds because it is an easy measure of species or stocks that have typically been doing poorly in the past, but we recognize that documents (Miller et al. 2009) already exist that communicate this information. Thus this indicator may not be necessary in a final status report of the CCLME.

Population condition—From the five indicators in the top quartile for population condition, we propose to use these two as indicators for population condition of groundfish in the CCLME:

- Age structure of populations
- Spatial structure of populations

These indicators were two of the top three indicators evaluated. We did not choose rebuilding timeline as one of the final indicators because it is only available for species which have been formally considered overfished; thus it is only useful for a small number of species that are already in poor shape. Using age structure accounts for many of the ecological processes that would affect age at maturity, so we felt age at maturity could be eliminated from the final suite. However, due to time constraints for this report, we have been unable to analyze age structure data for the groundfish community. Therefore, we have substituted size structure of populations as a proxy for age structure. This indicator was not in the top quartile for population condition, but it was the top-ranked indicator in the second quartile and missed the top quartile by 0.03

points. Because we are including size structure of populations in this iteration of the IEA, we decided it would be redundant to include mean length of species.

Size structure of populations. The mean size of all species caught in either fishery-independent surveys, fishery-dependent surveys, or landings is thought to be a useful and simple indicator to evaluate the overall effects of fishing (e.g., changes in rates of mortality) on an ecosystem (Fulton et al. 2005, Link 2005, Coll et al. 2009). Size-based metrics respond to fishing impacts because body size determines the vulnerability of individuals, populations, and communities (Jennings and Dulvy 2005). Others contend, however, that there are very few examples where length-based analysis leads to useful management advice, in part because of the need for age and gear selectivity information, and because size related changes in distribution will influence data (Hilborn and Walters 1992). Size-based metrics are thought to better support medium-term rather than year-to-year management evaluation, because they are unlikely to be appropriate for detecting responses to management action on time scales less than 5 years, and the response to management action often cannot be quantitatively interpreted for contributing causal factors without extensive additional research (Jennings and Dulvy 2005).

Fish population size structure has been linked to scientifically defined reference points or progress targets. Some have based these on a decline in mean size of greater than 30% (warning or precautionary threshold) or greater than 50% (limiting reference point), the latter of which was chosen because it corresponds to an observed doubling in the time series of length after fishing has decreased (Link 2005). Others suggest that practical issues currently preclude the development and adoption of firm reference points for size-based indicators, although an appropriate target would be a reference direction that is consistent with a decline in the overall human impacts of fishing on the community, and thereby on the ecosystem (Jennings and Dulvy 2005).

The principal attraction of size-based metrics is the widespread availability of species size and abundance data collected during ongoing monitoring programs (Jennings and Dulvy 2005). In the North Pacific, trawl survey data have been collected since 1998 under the annual/triennial groundfish surveys (Keller et al. 2008), where up to 100 length measurements, sex determinations, and individual weights, and up to 25 age structures continue to be collected per haul for key species, and more recently for all groundfish species of management concern. These surveys encompass a broad range of depths (55 to 1,280 m) and a vast geographic range from Cape Flattery, Washington, (lat 48°10′N) to the U.S.-Mexico border (lat 32°30′N). There are well recognized gear-selectivity issues associated with size data (Hilborn and Walters 1992) and ideally indicators should be calculated for size classes that are well selected by the gear. Fish population size structure has been used as an indicator in a variety of other ecosystems, including the Celtic Sea (Blanchard et al. 2005), northeastern U.S. continental shelf (Link and Brodziak 2002), and eastern Bering Sea (AFSC 2009).

Salmon

Population size—We identified, evaluated, and propose these three indicators for salmon in the CCLME:

- Spawning escapement

- Population growth rate
- Hatchery contribution

These indicators are supported by all of our primary literature resources (e.g., Lindley et al. 2009b, PFMC 2010a). Each indicator was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

Population condition—We identified, evaluated, and propose these three indicators for salmon in the CCLME:

- Age structure
- Spatial stock structure
- Size at age

These indicators are supported as indicators of population condition by all of our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each indicator was chosen based on length of times series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

Green sturgeon

Population size—We identified, evaluated, and propose these two indicators for green sturgeon in the CCLME:

- Spawning escapement
- Juvenile abundance

These indicators are supported by primary literature resources (e.g., Adams et al. 2007).

Population condition—We identified, evaluated, and propose these two indicators for green sturgeon in the CCLME:

- Age structure
- Spatial structure of stocks

These indicators are supported as indicators of population size primary literature resources (e.g., Adams et al. 2007).

Ecosystem health

Community composition—From the 18 indicators in the top quartile for community composition, we propose to use these four as indicators in the CCLME:

- Zooplankton species biomass anomalies
- Taxonomic distinctness (average and variation)
- Top predator biomass

- Seabird annual reproductive output

We selected two indicators (zooplankton species biomass anomalies and taxonomic distinctness) from the top quartile of the community composition attribute to represent ecosystem health in the CCLME, as well as two indicators (seabird annual reproductive performance and top predator biomass) that did not initially score in the top quartile (yet were in the top 30th percentile), but complemented the suite.

Two zooplankton indicators scored highest during the evaluation process: zooplankton species biomass anomalies and zooplankton abundance/biomass. We selected zooplankton species biomass anomaly over zooplankton biomass because of the relative benefits associated with having sentinel taxa guide indicator performance. Of the four diversity indices in the top quartile (adult sablefish biomass, Hurlbert's delta, IUCN number of threatened species, and taxonomic distinctness), we selected taxonomic distinctness for two reasons: 1) adult sablefish biomass and IUCN number of threatened species are correlates of diversity, but not actual measures of diversity, and 2) taxonomic distinctness has minimal data requirements that allow the integration of data sets, use of historical data, and data sets of varying quality.

We decided to exclude many of the groundfish-based indicators from the community composition attribute due to their inherent overlap with the groundfish component. We also passed over the salmon smolt-adult survival rate indicator for a similar reason, related to the salmon goal. Many of the groundfish indicators (groundfish status and trends, flatfish biomass, roundfish biomass, demersal fish biomass, rockfish biomass, proportion of noncommercial species, juvenile rockfish, and hake abundance) scored particularly well in part because of their strength regarding data considerations.

To supplement the suite of indicators that best characterized ecosystem structure, we added two indicators that focused on upper trophic levels of the CCLME: seabird annual reproductive performance and top predator biomass. Each indicator scored just below the top quartile (score = 8.1, top quartile = 8.25); thus there is good support in the literature for these indicators. In addition, our initial inventory of seabird colony monitoring programs underestimated the availability of long-term time series spanning the CCLME, which led us to reevaluate the potential utility of this indicator and its inclusion in the final suite. We describe the full evaluation of each indicator below.

Top predator biomass. The role of top predators in marine ecosystems has been the subject of numerous high-profile studies (e.g., Pauly et al. 1998, Myers and Worm 2003), while top predators are also of great societal interest (e.g., great white sharks [*Carcharodon carcharias*] and killer whales [*Orcinus orca*]). Typically, removing top predators from an ecosystem results in a trophic cascade (Strong 1992) in which populations of prey species increase in numbers because they are released from predatory control (e.g., Estes and Duggins 1995, Estes et al. 1998, Ward and Myers 2005). In many instances, this process cascades to the lowest trophic levels: phytoplankton (Frank et al. 2005, Casini et al. 2008). When top predators are able to rebuild (due to regulatory or management actions), prey species are once again controlled and the composition of the community reverts back to the initial state (e.g., otters, urchins, and kelp, Estes and Duggins 1995). Reference points for this indicator are easily defined and Link (2005) describes potential reference levels.

During the evaluation of this indicator, we defined top predator as any species with a trophic level equal to or greater than 4.0. Thus top predators span many taxa and may be monitored for estimates of biomass using various methods. Data for groundfish species are available from 1977 to 2010 in the WCGTS (see Groundfish, Population size, *Stock assessment biomass* subsection above). Time series data for marine mammals are available for a limited number of species from multiple sources which generally report numbers of individuals (Carretta et al. 2010). Fishery-independent time series data for benthic and pelagic sharks generally do not exist (except for spiny dogfish [*Squalus acanthias*]) and the fishery-dependent data are generally inadequate for formal stock assessments. Commercial landings data are available for a few species in the CCLME and might provide some insight into coarse trends over time with all the caveats of fishery-dependent data implied (see Hilborn and Walters 1992). The SWFSC performs an annual juvenile longline survey that typically catches shortfin mako (*Isurus oxyrinchus*) and blue sharks (*Prionace glauca*) with the occasional thresher shark (*Alopias vulpinus*).

The abundance and trends of top predators are easy to understand and are usually of interest to the public and policy makers. Due to the potential for trophic cascades with declines in top predator biomass (e.g. Estes and Duggins 1995, Estes et al. 1998, Ward and Myers 2005), this could be a leading indicator for changes in overall community composition of the CCLME.

Seabird annual reproductive output. Seabirds have frequently been identified as good indicators of the health and status of marine ecosystems because they are sensitive to variations in food supply and relatively easy to observe (Furness and Camphuysen 1997, Frederiksen et al. 2007, Piatt et al. 2007). Seabird reproductive performance tends to be a useful indicator of ecosystem conditions because it integrates useful information throughout the initiation of egg-laying through chick-rearing each year. As a result, seabird breeding failures often provide an early indicator of declines to marine forage fish populations, and related demographic parameters, such as seabird production and population trends, have been correlated with large scale indices of ocean climate, such as temperature or the Southern Oscillation Index (Sydeman et al. 2001, Montevecchi 2007, Piatt et al. 2007).

Costs for conducting long-term seabird colony monitoring programs are high. As a result, there are only a handful of seabird colony sites along the Pacific coast with long-term monitoring programs in place. Fortunately, the spatial scale of existing colony monitoring projects ranges from British Columbia to Southern California (including the Washington and Oregon coasts) and the monitoring often focuses on similar species. The availability of this information is highly variable, ranging from highly accessible, Web-based tables (e.g., Point Reyes Bird Observatory [PRBO] and Columbia River estuary) to currently inaccessible. Some recent projects have used these data sets as indicators of ecosystem condition (Sydeman and Thompson 2010), but the reliability of any individual parameter (e.g., breeding success of a particular species at one site) may also be affected by other drivers (e.g., local predation) (Frederiksen et al. 2007). However, a multivariate approach (Frederiksen et al. 2007) may be used to integrate data sets from a variety of species (both piscivorous and zooplanktivorous) from all of the long-term seabird colony monitoring programs along the Pacific coast. This combined index would use the breeding performance of a variety of seabird species along the Pacific coast as a general indicator of the health of the CCLME, in terms of providing sufficient food for breeding seabirds to raise their young. It is expected that the availability of data sets will improve as this index is developed and disseminated.

Energetics and material flows—From the three indicators in the top quartile for energetics and material flows, we propose to use these two in the CCLME:

- Chl a
- Inorganic nutrient levels (phosphate, nitrate, silicate)

Both indicators not only scored well with regard to our evaluation considerations, but also can be used in the near term with readily available data to evaluate drivers that affect fundamental processes. Number of cycles, a third indicator that describes carbon cycling, also scored in the top quartile and holds promise for inclusion in the near future as existing mass-balance models (Brand et al. 2007, Horne et al. 2010) are further developed, tested, and validated.

Future Criteria

In future iterations of the California Current IEA, we propose to include other formal criteria during the ranking of potential indicators to quantify the quality of science supporting each indicator during the evaluation process. Although not completely developed, these criteria will categorize the literature cited as: 1) peer-reviewed literature, 2) government document, or 3) gray literature. These categories of literature will be given a rating value between 0 and 1. In addition, peer-reviewed literature will receive an additional rating based on the impact factor of the publishing journal. These values will be summed, averaged, multiplied by the weighting of each criterion, and summed across each indicator to produce a score for the quality of science supporting each indicator.

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Groundfish, Salmon, Green Sturgeon, and Ecosystem Health

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